USACE Extreme Sea levels

Progress Report 1 ~ Approved for Public release; Distribution unlimited.

14th March 2014

HR Wallingford Project Number: MCR 5156

Introduction

HR Wallingford and Southampton University are supporting the USACE in the development of an Engineering Technical Letter (ETL), in relation to extreme sea levels and climate impact adaptation. Lead personnel responsible for the USACE are Dr Kathleen White and Heidi Moritz. The work to be undertaken during this research effort includes:

1) Undertaking research to identify the underlying fundamental nature and influences of changes in extreme sea levels as they affect the four mission areas of USACE: storm damage reduction, flood risk mitigation, ecosystems management and navigation.

2) Involvement as appropriate in regular telephone conference calls with the ETL project team.

3) Production of one or more conference and/or peer-reviewed journal papers to disseminate the work.

4) Attendance at two ETL project meetings

5) Preparation and submission to IWR of a final report summarising the results of the research, together with a set of recommendations arising from the research.

This report describes progress to date (March 2014) on the project.

Progress

Progress to date comprises 4 main activities described below:

1 Meeting between HR Wallingford and Southampton University at HR Wallingford and subsequent teleconference with Heidi Moritz and Kate White. The notes summarising the findings of the meeting are provided below.
2 Preparation for and attendance of Ben Gouldby and Jonathan Simm at a workshop in Washington, in February 2014. The agenda for the workshop is provided below. Presentations documents are attached.
3 A technical note produced by Southampton University (Ivan Haigh) that provides an overview of current practice on extreme sea levels in the UK, Australia and Germany. This technical note is attached to this progress report.
4 Jonathan Simm has engaged in discussions with Hiedi Moritz and Kate White, regarding the formulation and role of a steering group to oversee the project.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **14 MAR 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**
4. TITLE AND SUBTITLE **USACE Extreme Sea levels**		5a. CONTRACT NUMBER **W911NF-13-1-0183**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **HR Wallingford,Howbery Park,Wallingford, UK,**		8. PERFORMING ORGANIZATION REPORT NUMBER **; 1604-EN-01**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Army Engineer Research & Development Center - International Research Office, ERDC-IRO, ATT: RICHMOND, Unit 4507, APO, AE, 09421**		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S) **1604-EN-01**
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**60**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Initial Discussion Regarding Investigation into Extreme Water Level Characterization
9 September 2013

Attendees: Heidi Moritz, Kate White, Jonathan Simm, Robert Nicholls, Peter Hawkes, Ivan Haigh

Primary areas of discussion:

- Initially separating the investigation of extreme water levels from storm climate.
- Characterization of storms and the storm climate along with expected changes due to climate change. (tropicals and extra-tropicals)
- Characterizing past and current extreme water levels prior to adding expected future conditions. Using extreme water level characterization to help explain the expected loading condition prior to looking into adaptation.
- Determining how to make a historical analysis of extremes and surges transferable to the future including effects of expected climate change and the appropriate description of uncertainty.
- Defining categories of extreme events with appropriate descriptive parameters. Breaking down loading into components of water level and components of storms. Include alongshore spatial distribution of extreme loading.
- Current work being conducted for Hurricane Sandy Comprehensive Report.
- Recommended approach to work effort products and socializing the subject matter information in the US.

1. Initially separating the investigation of extreme water levels from storm climate.

The suggestion was made that we may want to begin talking about extreme water levels separate from storms. Ivan mentioned an analysis of storminess which tried to identify how much of an increase in storminess might be needed to be of a similar impact as an increase in sea level. Findings were that a linear increase in sea level had much more significance than an increase in storminess.

2. Characterization of storms and the storm climate along with expected changes due to climate change. (tropicals and extra-tropicals)

Ivan provided some good information on work being done on tropical storms in Australia. Jeff Arnold (USACE-IWR) is currently working with a team of people on the analysis of climate impacts on storms and storminess. Some of this work is being used to support the post-Hurricane Sandy work.

3. Characterizing past and current extreme water levels prior to adding expected future conditions. Using extreme water level characterization to help explain the expected loading condition prior to looking into adaptation.

Robert Nicholls raised the question of how well do we feel that we understand the present extreme climate? We should start with this area including historical data, data completeness, stationary projections. Jonathan mentioned some UK work that has been looking at SWL

characterization along the UK coast including wave set-up and run-up. One goal should be to provide a reasonable way to look at extreme water levels and statistical methods; including extremes, combinations. Once we have that well-defined, we can move on to what might climate change be changing? There was general support for sorting out what the loadings are rather than the adaptation to the loadings at this time.

The recent Environment Agency reports on extreme sea levels around the UK can be found at the webpage below. Unfortunately, most of the results are not publicly available, and are intended to be accessed only through a personal and site-specific request to the relevant person at the Environment Agency.
http://evidence.environment-agency.gov.uk/FCERM/en/Default/HomeAndLeisure/Floods/WhatWereDoing/IntoTheFuture/ScienceProgramme/ResearchAndDevelopment/FCRM/Project.aspx?ProjectID=f162d56f-87c4-4f14-b77b-a8a3efdb363f&PageID=3679217f-8f79-4c83-b935-f277aaadbdf1

4. Determining how to make a historical analysis of extremes and surges transferable to the future including effects of expected climate change and the appropriate description of uncertainty.

The Sea Level Change Technical Letter currently uses the Kriebel method as a first estimate of SLC impacts on future extremes. This method uses a fairly straight-forward approach of simulating historical storm tides on future sea levels. Some parameters that we can include are extremes of surges and changed wave action and potentially changing storm parameters.

We should also consider whether it is worth doing any more to represent climate change effects on extreme sea levels than just to add the mean sea level future change allowances.

5. Defining categories of extreme events with appropriate descriptive parameters. Breaking down loading into components of water level and components of storms. Include alongshore spatial distribution of extreme loading.

An Australian investigation into categories of extreme events was discussed. They used global meteorological data to help define 5 distinct types of storms, including different types of surge events. Both short and long duration events are included in the analysis. The varying consequences of different types of events were discussed in general including the various parameters that help us define events: water levels, wave height and period, storm duration, storm power. A sensitivity analysis can be conducted to help define how the different parameters contribute to the consequences and how important are they? Hypotheticals can be developed based on the 5 categories. Are the storms/events that we are using now representative?
Some additional UK work analyzing the spatial distribution of extremes was discussed including discussion of different storm/event tracks. How do we describe the spatial distribution of the surge footprint?

John Hunter (University of Tasmania, Australia) has been conducting work in defining the uncertainty related to sea level change and extreme water levels.

6. Current work being conducted for Hurricane Sandy Comprehensive Report.

Some discussion occurred regarding the water level analysis being conducted in the post-Hurricane Sandy studies. The results appear to provide a stationary distribution over the next

100 years and there is some concern that the non-stationarity aspects as well as the true potential range of extremes may not be captured in the results. Kate and Heidi will follow up with the Hurricane Sandy team.

7. Recommended approach to work effort products and socializing the subject matter information in the US.

Kate's recommended approach is to try to work toward the development of 2 journal papers and an Engineering and Construction Bulletin (ECB). Jonathan asked about the possible time it may take to make it through the peer-review and acceptance process for a journal paper. Robert suggested that most of the papers which are needed for an analysis today may be already written although they may be UK or Australia – centric. Kate would like that approach expanded to include the US in order to socialize the ideas and concepts. We can also identify any gaps or areas that need more work.

Action Items:

- Jonathan will send a list of people (with emails) that might be helpful for the extreme water level analysis review and discussion for the Hurricane Sandy Comprehensive Study
- Kate and Heidi will discuss with Jason Engle and determine the best way to proceed.
- Kate will provide a copy of the storm climate analysis report that Andy Garcia and his group were working on.
- Heidi and Jeff Arnold will connect Jeff Arnold's group with the Australian group regarding the climate effects on storm climate.
- Kate and Heidi will connect the group in Australia (Ron Cox, Bill Pierson) and Rod (USACE) with this group.
- NOAA (Steve Gill, Chris Zervas, Billy Sweet) and USNA (Dave Kriebel) will be included.
- Jonathan Simm will be out of contact most of the time between 17 September and 16 October 2013. During that time please treat Peter Hawkes as the first point of contact at HR Wallingford.

Additional contacts/work efforts to include as applicable:
Australian, German, US, and UK investigations

USACE EXTREME WATER LEVEL TECHNICAL LETTER DEVELOPMENT
U.S. Army Corps of Engineers
Engineering Technical Letter – Team Meeting
Date: 18-19 February 2014

Location: New York District Office, New York
Planning Division Conference Room, 21st Floor, Room 2138
26 Federal Plaza, USACE Entrance on Duane Street
2nd Building entrance east of Broadway

Tuesday, 18 February

12:00 to 12:15: *Welcome and Introductions* (Heidi Moritz, USACE**)**

12:15 to 12:25: *EWL Technical Letter and Responses to Climate Change Program* (Kate White, USACE)

12:25 to 12:40: *Coastal Working Group Survey Results* (Tom Smith, USACE)

12:40 to 12:50: *ETL Purpose and Expected Products* (Heidi Moritz, USACE**)**

12:50 to 1:10: *USACE Existing Guidance on EWLs* (Jessica Podoski, Will Veatch, USACE)

1:10 to 1:35: *USACE Current Practice for EWL Incorporation into Project Design* (Jessica Podoski, Will Veatch, Hans Moritz, Patrick O'Brien, USACE)

1:35 to 2:05: *Federal Agencies Approach/Products related to EWLs*
- **NOAA** (Billy Sweet, Chris Zervas)

2:05 to 2:25: Break

2:25 to 3:10: *Federal Agencies Approach/Products related to EWLs*
- **USGS** (Curt Storlozzi)
- **FEMA** (Mark Crowell, Brian Batten)

3:10 to 4:10: *International Approaches to EWLs*
- **United Kingdom** (Ben Gouldby)
- **Australia** (Bill Peirson)
- **Germany** (Thomas Wahl)

4:10 to 4:35: *ERDC Approach to Statistical Characterization of Extreme Water Levels with Sea Level Change* (Jeff Melby, USACE-ERDC)

4:35 to 5:30 Summary and Wrap-up, Agenda for Wednesday

EXTREME WATER LEVEL ASSESSMENT
U.S. Army Corps of Engineers
Engineering Technical Letter – Team Meeting
Date: 18-19 February 2014

Wednesday, 19 February

8:30 to 8:55: *Components of Extreme Water Level and WL Component Superposition* (Peter Ruggiero, Oregon State University)

8:55 to 9:40: Discussion and EWL Products – Components of Extreme Water Level

9:40 to 10:10: *Categories and Description of Extreme Events* (Ivan Haigh and Thomas Wahl, University of Southampton, University of Siegen)

10:10 to 10:55: Discussion and EWL Products – Categories and Description of Extreme Events

10:55 to 11:15: Break

11:15 to 11:40: *South San Francisco Bay and Stamford, Connecticut Project Examples* (Patrick O'Brien and Mark Huber, USACE)

11:40 to 12:25: Discussion and EWL Products – Characterization of EWL vs Project Risk Assessment and the use of Confidence Limits

12:25 to 12:50: *Application of a Multivariate Extreme Value Method for Spatially Coherent Coastal Flood Risk Analysis* (Ben Gouldby, HR Wallingford)

12:50 to 2:00: Lunch

2:00 to 2:25: *Best Practices and Analysis Methodologies* (Jeff Melby, USACE)

2:25 to 3:10: Discussion and EWL Products – Best Practices and Analysis Methodologies

3:10 to 3:30: Break

3:30 to 4:15: Discussion - *Required Design, Planning, and Risk Assessment Products and Tools for Technical Letter- USACE*

4:15 to 5:30 Discussion, Plan and Schedule for EWL ETL Development; Assignments

5:30: Adjourn

Best-practice approaches for estimating extreme sea-level probabilities along complex topographic coastlines: Examples from the UK, Germany and Australia

Ivan D. Haigh[1,2] and Thomas Whal[3,4]

[1]Ocean and Earth Sciences, National Oceanography Centre, University of Southampton, European Way, Southampton, SO14 3ZH, UK. E-mail: I.D.Haigh@soton.ac.uk

[2] School of Civil, Environmental and Mining Engineering and the UWA Oceans Institute, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.

[3]Research Centre Siegen, University of Siegen, Hagener Str. 139, 57072, Siegen, Germany. Email: Thomas.Wahl@uni-siegen.de

[4]College of Marine Science, University of South Florida, 140 7th Avenue South, St. Petersburg, FL 33701.

Document produced for the Extreme Water Level Workshop to be held in New York in February 2014

DRAFT

1.0 Introduction

When significant coastal flooding occurs along low lying, highly populated, and/or developed coastlines, the impacts can be devastating and long lasting with wide ranging social, economic, and environmental consequences. These include: considerable loss of life; deterioration of health conditions owing to waterborne diseases; billions of pounds worth of damage to property and coastal infrastructure; disruptions to supply chains; and drastic changes to coastal landforms (Lowe et al., 2010). Several significant events in the last decade, for example: Hurricane Katrina in New Orleans in August 2005; Cyclone Xynthia on the French Atlantic coast in 2010; Hurricane Sandy in New Jersey in 2012; and most recently Typhoon Haiyan in the Philippines in 2013; have dramatically emphasized the high vulnerability of densely populated coastlines to extreme high sea level events, in different parts of the world.

Coastal flooding is nothing new. Throughout history, settlers, attracted to flat and fertile coastal plains, would have had to adapt to periodic coastal flooding. However, as a society we have become increasingly vulnerable to extreme high sea level events as our cities and our patterns of coastal development become more intricate, populated and interdependent (Pugh 2004; Nicholls et al. 2007). In addition, there has also been growing concern in recent decades about rising sea levels (Church et al., 2013), as these have the potential, along with possible changes in the frequency, magnitude and tracks of storms, to increase the likelihood of coastal flooding around the world (Lowe et al. 2010; Seneviratne et al. 2012). With sea-level rise and changes in storminess, given high sea levels will be exceeded more frequently over the coming century. Without appropriate adaptive measures this will significantly impact extensive coastal populations, infrastructure and trade around the world. Therefore it is vital that the probabilities of extreme water levels are accurately evaluated to inform risk-based flood and erosion management and future land-use planning. Ensuring they are accurately estimated is crucial to prevent catastrophic structure failures due to under-design or expensive wastes due to over-design (Haigh et al., 2014a).

Over the last five decades, several different extreme value analysis methods for estimating probabilities of extreme still water levels have been developed (see Haigh et al., 2010a for an overview). However, there is currently no universally accepted method available. Instead, different methods have been applied not only on transnational, but also on national scales, resulting in potential inconsistencies in estimates between different regions and hence a heterogeneous level of protection (Batsone et al. 2013). Applying different statistical methods can yield significantly different estimates of return water levels, but even the use of the same method can produce large discrepancies, because there is subjective choice at several steps in the model setup (Arns et al., 2013).

In the last few years, the need for national consistency and improved and updated estimates of extreme sea-level probabilities, has led to the production of databases that provide extreme sea levels probabilities continuously around entire coastlines of countries. Here we briefly summaries three such studies that have been undertaken recently for the:

- United Kingdom (UK) - Macmillan et al., 2011; Badstone et al., 2013;
- Germany - Arns et al., 2013, 2014); and
- Australia - Haigh et al., 2014a,b).

Note the authors of this document have lead or been involved in the later two studies, but were not directly involved with the first (although Ivan Haigh did formally review the first study).

Traditionally, exceedance probabilities for extreme still water levels, which arise as a combination of three main factors: astronomical tide, storm surge and mean sea level (MSL) (Pugh 2004) (wind-waves can further elevate coastal sea levels, see O'Grady and McInnes (2010), but their effects are not considered here), have been calculated from tide-gauge measurements. However, as Haigh et al. (2014a) point out, there are two main problems with this approach preventing accurate estimates of exceedance probabilities continuously around a coastline. First, there are typically only a few tide gauge sites located around the coastline of countries with records long enough (~30 years) to accurately estimate exceedance probabilities using conventional extreme value analysis methods (Haigh et al., 2010). As the characteristics of extreme water levels can vary considerably around complex topographic coastlines, a simple interpolation of probabilities between the sometimes widely spaced tide gauge sites does not provide an accurate spatial representation of extreme levels. Second, the probabilities of extreme water levels caused by intense tropical cyclones cannot be estimated solely using tide gauge records. Even in records covering many decades to a century, there are typically only a few observations of large tropical cyclone-induced water levels and these are often significantly higher than any other recorded level. This occurs because the low spatial density of tides gauges means it is relatively rare that a tropical cyclone will pass close enough to a gauge site to generate extreme levels. Indeed, for any particular event it is likely the highest storm surge will not be measured by a tide gauge. Also, the response of generated high water levels is complex, localized and dependent on the timing of the astronomical tide (Harper 2001). Hence, using the observational record only to make extrapolation to low probabilities of occurrence is inadequate (McInnes et al. 2009). We describe how the studies undertaken for the UK and Germany addressed the first issue (the second issue is not a problem in those two countries because they do not experience tropical cyclones) and how the study carried out for Australia addressed both of these two issues.

2.0 United Kingdom

The UK has a long history of severe coastal flooding. In 1607, between 500 and 2,000 people were drowned in isolated farms and villages on low-lying coastlines around the Severn Estuary and Bristol Channel (Horsburgh and Horritt, 2006). This coastal flood caused the greatest loss of life from any sudden onset natural catastrophe in the UK during the last 500 years (RMS, 2007). During the so-called 'Great Storm' of 1703, hundreds of people were drowned along the southern coast of the UK and the lowermost street of houses in the village of Brighthelmstone (today's Brighton) was washed away (RMS, 2003). In January 1928, several riverside districts in London were flooded, drowning 14 people. In 1953, the disasters of coastal flooding were brought to the forefront by a severe North Sea storm (Rossiter 1954; McRobie et al. 2005) during which 307 people were killed in southeast England, and 24,000 people fled their homes (Jonkman and Kelman 2005), while 1,835 lives were lost in the Netherlands (Verlaan et al. 2005). These extreme storms and resulting coastal floods, especially the 1953 event, led to wide-spread agreement on the necessity of a coordinated response to understanding the risk of future coastal flooding and to provide protection, where possible, against such events (Coles and Tawn, 2005). The 1953 event in particular, was the driving force for the development of the Thames Storm Surge Barrier in London and also lead to the establishment of storm surge forecasting services (Heaps, 1983). Without the Thames Barrier and associated defences, London's continued existence as a capital and a major world city would be precarious (Dawson et al., 2005). Today, more than 2.5 million properties and £150 billion of assets are potentially exposed to coastal flooding in the UK.

In the 60 years since the 1953 event, there have been many assessments that have estimated extreme extreme sea-level probabilities for the UK. The first studies were undertaken by Lennon (1963) and Suthons (1963), and then Graff (1978). They used the annual maximum method to estimate return sea levels at tide gauge sites, but they were limited by data availability and the range of statistical models and inference techniques that were then available (Coles and Tawn, 2005). Following that Pugh and Vassie (1979, 1980) developed the joint probability method (JPM) and applied this to records at UK tide gauge sites. This approach involved separate analysis of the astronomical tide and non-tidal residual, followed by a convolution to obtain the probability distribution of the sum. The advantage of the JPM was that return levels could be estimated from relatively short records (<5 years), but the method had three main inadequacies (see Haigh et al. 2010 for details). Tawn and Vassie, (1989) and Tawn (1992) made two principle improvements to the JMP, which make it more widely applicable, and in the process developed the revised joint probability method (RJPM).

In more recent times, different Environment Agency (EA) regional departments estimated extreme probabilities, for the area for which they were responsible, using a wide range of the different approaches described above (see Swift, 2003 for a review of these). However, on behalf of the EA, Dixon and Tawn (1994, 1995, 1997) provided the first coherent estimate of extreme still sea-level probabilities at high resolution all around the UK coastline using their so called 'Spatially Revised Joint Probability Method' (SRJPM). The SRJPM extended the RJPM by exploiting knowledge of the spatial variation of the tidal and surge components of the sea level around the UK and incorporating all the types of data available (annual maxima, hourly values and data from the CSX numerical storm surge model). A key output of the study was a set of tables containing return level estimates, relative to the 1 in 1 year return level, for a regular grid around the UK. Estimates of extreme sea level can be made at any location around the UK by simply combining these relative levels with a 1 year return level, calculated using one of the methods mentioned above.

There were two main shortcomings associated with the SRJPM estimates. First, the method resulted in over prediction of extreme sea levels along most of the UK south coast. This was mainly due to the comparatively short (< 5 years) datasets originally used to calibrate the model in this area (Haigh et al., 2010). Secondly, around large parts of the UK there are considerable non-linear interactions between the tidal and meteorological induced components of sea level (Horsburgh and Wilson, 2007). The RJPM and SRJPM accounted for this by modelling the surge distribution conditional on the state of the tide. However, this relationship is complex for all shallow water sites and was a considerable source of uncertainty in these methods.

To overcome these shortcomings a major update to that national study has recently been completed by Macmillan et al. (2011; which is also described in Badstone et al., 2013). To avoid problems associated with the way tide-surge interaction was handled in the RJPM they developed a new joint probability method, which they called the Skew Surge Joint Probability Method (SSJPM). This makes use of the 'skew surge' parameter, which is the absolute difference between the maximum recorded sea level during a tidal cycle and the predicted maximum astronomical tide. The skew surge parameter is a more reliable indicator of meteorological impacts on sea-level than the non-tidal residual used in the RJPM and SRJPM. In the first stage of their study, they used the SSJPM, with the longer tide gauge records that are now available, to estimate extreme sea-level probabilities at around 45 sites around the UK. In the second stage, they made use of a 44-year modeled hindcast of sea-levels (produced by forcing the CS3X north European shelf model with

gridded pressure and wind fields from the ERA40 meteorological reanalysis; Uppala et al., 2005) to dynamically interpolate these estimates at the tide gauges sites, around the whole coastline of the UK at 12km resolution (Fig. 1).

3.0 Germany

Germany has a particularly long history of severe coastal flooding, with information on the occurrence of such events going back more than 2,000 years (the so-called 'Crimbian Flood' occurred 340 B.C., other sources suggest it was more likely 120 B.C.). More detailed information on significant events (e.g. affected coastline stretches, number of fatalities) go back more than 1,000 years (see Jensen and Müller-Navarra (2008) and references therein). During one of the biggest North Sea storm surges in 1362 (known as the Second Marcellus Flood) more than 100,000 people died and the wealthy port city of Rungholt on the Island Strand sank and became famous as the 'Atlantis of the North Sea'. During a storm surge on November 1570 (the Fourth All Saints' Flood) between 100,000 and 400,000 people were drowned (Lamb 1991); another significant event in 1634 (The Great Drowning) caused ~15,000 fatalities and major parts of the Island Strand disappeared.. The most devastating event in the last century occurred in February 1962 (The Hamburg Flood) when 315 people lost their lives (Butow 1963; von Storch and Woth 2006). After the experiences already made in 1953 it was this event that motivated significant investments and upgrade of coastal defences. The upgraded system proofed its efficiency during the 1976 storm surge which led to the highest water levels ever recorded along major stretches of the coastline but caused relatively small damages.

The German coastline nowadays has a total length of around 1,500 km with the two federal states Lower Saxony and Schleswig-Holstein directly bordering the North Sea and Hamburg and Bremen being situated along tidal rivers (Elbe and Weser) strongly influenced by North Sea extreme sea level events (Fig. 2). Coastal protection in Germany is organized by government departments in these federal states and design water levels are defined using different approaches: Lower Saxony and Bremen use a deterministic approach, i.e. the highest observed surge is added (linearly) to the highest astronomical tide (NLWKN, 2007). Design water levels in Hamburg are based on a design surge derived from the observations at the tide gauge Cuxhaven, combined with a spring tide (tide-surge interaction is considered) and external surge (triggered in the north Atlantic and entering the North Sea); the total water levels are then transferred from Cuxhaven to Hamburg in the Elbe Estuary with a hydrodynamic model (Gönnert et al., 2013). In Schleswig-Holstein design water levels have a return period of 200-years and are derived from the highest water levels observed in a year (AMAX) with extreme value analysis (EVA; LKN, 2012). The EVA model setup is not further specified leaving a considerable risk of subjectively influencing the return water level estimates. All three states account for potential future sea level rise of 50cm (linearly added to the design water levels). Due to the inconsistency in the applied methods, it is difficult to assess the level of protection offered by defences across the different federal states and equally difficult to compare this with defences in the neighboring countries Netherlands and Denmark, who also use different (statistical) techniques.

Recently, Arns et al. (2013, 2014) estimated extreme sea-level probabilities all around the northern coastline of Germany by following different steps. First, they estimated and compared probabilities of extreme sea levels at tide gauges, primarily in the Germany Bight, systematically considering a wide range of strategies to estimate these probabilities and a range of different model setups. They focused on testing the influence of the

following three main factors, which can affect the estimates of extreme value statistics: (1) detrending the original data sets (i.e. accounting for long-term sea level rise and seasonal fluctuations); (2) building samples of extreme values from the original data sets (i.e. using block maxima with AMAX or the r-largest values per year, or peaks over threshold); and (3) the record lengths of the original data sets (i.e. how long must a record be. They focused on direct methods where the observed total water levels are directly analysed instead of separating the tide and the surge (as it has been done in the UK for example). This approach is preferred since tide gauge records with a temporal resolution high enough to apply tidal analysis techniques are relatively short. For most tide gauges only 15 to 20 years or less of (digital) high frequency data is available, but tidal high and low waters go back to the 1930s at many and the mid to late 19th century at selected sites. The final outcome of the study by Arns et al. (2013) was the recommendation of an objective approach, with as little subjectivity as possible, which could be applied routinely around the coastline of Germany, to help overcome the problem of heterogeneous levels of protection resulting from different methods and varying model setups. They found that a time series length of ~40 years (including information from the extreme 1976 event) was sufficient to calculate accurate return water levels. Hence, in a subsequent step they conducted a 40-year water level hindcast with a hydrodynamic numerical model to obtain the required information for each coastal grid point (~ every kilometer; the focus was on the coastline of Schleswig-Holstein) (Arns et al., 2014). Using the setup of the EVA model previously identified to be suitable for the area, they calculated return water levels for the entire coastline of Schleswig-Holstein, including the offshore islands from which no or only very sparse observational data is available (see Fig. 3). It is planned to extend the study to include the coastline of Lower Saxony.

In a research project XtremRisK (https://www.tu-braunschweig.de/lwi/hyku/xtremrisk/) integrated risk analyses were conducted for the city of Hamburg (or parts of it) and the biggest German North Sea Island Sylt (in particular the cities of Westerland and Hörnum). In this project multivariate statistical models were used to calculate the (joint) probabilities of the occurrence of a range of storm surge (and wave) events (Wahl et al., 2011, 2012), failure probabilities were determined, inundation models were applied, and damages in the hinterland were assessed (see Oumeraci et al., 2012 and references therein for an overview). Such risk-based approaches will likely become more important in the future but are not yet feasible to be applied widely to entire coastline stretches.

4.0 Australia

Like the US east coast, Australia has a long history of coastal flooding associated with tropical cyclones, with several major events recorded since the late 1880s (Harper et al. 2009). The largest death toll of any natural disaster in Australian history occurred in March 1899 when cyclone Mahina hit Bathurst Bay (Queensland), claiming the lives of over 300 people (Nott and Hayne 2000). More recently, cyclone Yasi (2011) battered the coastline of northern Queensland generating a storm surge of more than 5 m. Fortunately the cyclone made landfall away from densely populated areas and the coastal flood damage was limited compared with what would have occurred had it come ashore closer to the coastal populations of Cairns or Townsville. Given this risk, it is important that extreme sea level probabilities are accurately evaluated in this region and around the Australian coast. The need for such a study is exemplified by the fact that Australia has one of the longest coastlines in the world, approximately 85% of the population lives in coastal regions, and all state capital cities and much of the nation’s commercial activities lie within the coastal zone (DCC, 2009).

In the context of Australia, the majority of past studies that have estimated water level annual exceedance probabilities (AEP) have done so on local or regional scales (e.g. Harper et al. 2001, 2009 for Queensland; McInnes et al. 2003, 2009, 2011a for southeast Australia; McInnes et al. 2001b for Tasmania) and hence the current information is not up to date and consistent around the country. Further, a range of different modelling approaches has been used on different spatial resolutions. In addition, the coastline of Australia, similar to that of the US east coast (Zhang et al. 1997, 2000), is subject to both extra-tropical and tropical cyclones. Few, if any past studies in Australia have jointly estimated the probabilities of extreme water levels arising from both extra-tropical and tropical cyclones. Not surprisingly, the past studies that have produced multi-decadal hindcasts of water levels have all been for regions without tropical cyclone influence. Therefore, it is important to provide a coherent estimate of present day extreme water level probabilities around the whole coastline of Australia, arising from combinations of mean sea level, astronomical tide and storm surges generated by both extra-tropical and tropical cyclones.

The recent study for Australia was undertaken in a two-staged approach. In the first stage (described in Haigh et al., 2014a) the first issue (i.e. poor spatial coverage of long observational data sets) was addressed by constructing a hydrodynamic model of the Australian continental shelf region using the Danish Hydraulic Institute's Mike21 modelling tools (DHI, 2013). The model grid is shown in Fig. 5 and has a resolution of ~10 km along the entire coastline. The model was forced with astronomical tidal levels from the TPX07.2 global tidal model (Egbert and Erofeeva, 2002), and meteorological fields from the US National Center for Environmental Prediction's global reanalysis (Kistler et al., 2001), to generate a 61-year (1949–2009) water level hindcast. This dataset was validated against measurements from 30 tide gauges around Australia (see Fig. 4). Extreme sea-level probabilities were then estimated with the annual maxima method and related r-largest method, using the predicted water level time-series at each coastal grid point (Fig. 5a). This provided a reliable estimate of present day water level exceedance probabilities around southern Australia, a region mainly exposed to extra- tropical cyclones. However, while the spatial (2.5°) and temporal (6 hourly) resolution of the meteorological forcing was adequate for predicting extreme water levels associated with large extra-tropical cyclones, it was too coarse to accurately predict the more intense and localised tropical cyclone-induced events. As a result, the probabilities were underestimated around western, northern and north-eastern Australia, regions influenced by tropical cyclones. Even if the resolution of the meteorological forcing had been adequate to represent tropical cyclone-induced storm surges, multi-decadal periods still yield insufficient instances of tropical cyclones to enable the use of traditional extrapolation techniques.

In the second stage (described in Haigh et al., 2014b) the second issue (i.e. estimating probabilities of extreme water levels arising from tropical cyclones) was addressed. A statistical tropical cyclone model was developed to more accurately include tropical cyclone-induced surges in the estimation of extreme total water level probabilities. This model was then used to generate a 10,000 year synthetic tropical cyclone event set, based on characteristics of tropical cyclone activity over the last 40 years, for the Australian region. Wind and pressure fields were derived for these synthetic events and used to drive the hydrodynamic model. Annual maximum levels were calculated and used to estimate exceedance probabilities around the coast (Fig 5b). These estimates were combined with those derived from the multi-decadal hindcast to give a single estimate of present day extreme water level probabilities around the whole coastline of Australia.

All results from this work are freely available for download via a web-based tool (www.sealevelrise.info). Hunter (2010) developed a technique for combining the uncertainties in existing extreme water levels with the uncertainties in the projections of mean sea level rise. The results are given in the form of exceedance probability curves as a function of water level. Each curve represents the likelihood of one or more flooding events at a given height and location, over a specified period during the 21st century, under conditions of a prescribed emission scenario. Hunter (2011, 2013) described a simple extension of this technique which enables the objective choice of a vertical allowance for (regional) mean sea level rise (i.e. the amount by which coastal assets need to be raised), given the statistics of present extreme water levels and projections of mean sea level rise. The method preserves the expected frequency of flooding events if this allowance is applied as mean sea level rises. These techniques have been implemented into the abovementioned web-based tool.

We (Prof Chari Pattiaratchi – University of Western Australia; Ivan Haigh) have recently been awarded another follow-up project by the Australian Bush Fire Corporate Research Centre. This four-year study (2014-2017) is aimed at enhancing the study of Haigh et al. (2014a,b) by more accurately incorporating: (1) shelf waves; (2) metrological tsunamis; (3) the transition from tropical cyclones to extra-tropical storms; and (4) wave setup.

5.0 Summary

The three examples presented here outline what has been identified as the best practice (although not yet implemented in the guidelines everywhere) to calculate return water levels in the respective regions. It is obvious that there is a common approach to obtain results for coastline stretches where observational data are missing or sparse (i.e. the regionalization). With the computational capabilities we have nowadays and the information from atmospheric reanalyses (or tropical cyclone models) the preferred approach is to use well-developed hydrodynamic numerical models to produce water level information around/along the entire coastline. The EVA approaches on the other hand, which are then applied to the model output (and tide gauge observations) to derive the return water level estimates differ across countries and depend on (i) data availability (length and temporal resolution) and (ii) the type of storm events driving storm surges in the particular region (extra-tropical, tropical, or both).

References

Arns, A., Wahl, T., **Haigh, I.D.**, Pattiaratchi, C., Jensen, J., **2013**. Estimating extreme water level probabilities: a comparison of the direct methods and recommendations for best practise. Coastal Engineering, 81, 51–66.

Arns, A., Wahl, T., **Haigh, I.D.**, Jensen, J., 2014. Determining extreme water return levels at un-gauged sites: a case study of the Schleswig-Holsteins coastline and Islands in north-west Germany. In review Ocean Dynamics.

Batstone, C., Lawless, M., Tawn, J., Horsburgh, K., Blackman, D., McMillan, A., Worth, D., Laeger, S. & Hunt, T., 2013. A UK best-practice approach for extreme sea-level analysis along complex topographic coastlines. Ocean Engineering, 71, 28–39.

Bütow H (1963) Die große Flut in Hamburg. Eine Chronik der Katastrophe vom Februar 1962. Freie und Hansestadt Hamburg, Schulbehörde

Danish Hydraulic Institute (2010) Mike 21 & Mike 3 flow model FM, Hydrodynamic and transport module scientific documentation.

Coles, S., Tawn, J., 2005. Bayesian modelling of extreme surges on the UK east Coast. Philosophical Transactions of the Royal Society of London A363 (1831), 1387–1406.

Dawson RJ, Hall JW, Bates PD, Nicholls RJ (2005) Quantified analysis of the probability of flooding in the Thames Estuary under imaginable worst case sea-level rise scenarios. Int J Water Resour Dev Special Edition Water Disasters 21(4):577–591.

Department of Climate Change (2009) Climate change risks to Australia's coast: a first pass national assessment, p 168. Accessed 07/06/2012.
http://www.climatechange.gov.au/*/ media/publications/coastline/cc-risks-full-report.pdf

Dixon, M.J., Tawn, J.A., 1994. Extreme sea-levels at the UK A-class sites: site-by-site analysis. POL Internal Document Number 65. . (http://www.pol.ac.uk/ntslf/pdf/ id65.pdf).

Dixon, M.J., Tawn, J.A., 1995. Extreme sea-levels at the UK A-class sites: optimal site-by-site analysis and spatial analyses for the East Coast. POL Internal Document Number 72. . (http://www.pol.ac.uk/ntslf/pdf/id72.pdf).

Dixon, M.J., Tawn, J.A., 1997. Estimates of extreme sea conditions — final report, spatialanalysis for the UK coast. POL Internal Document Number 112. (http://www.pol.ac.uk/ntslf/pdf/id112.pdf).

Egbert GD, Erofeeva S (2002) Efficient inverse modeling of barotropic ocean tides. J Atmos Oceanic Technol 19(2):183–204.

Graff, J., 1978. Concerning the recurrence of abnormal sea-levels. Coastal Eng. 2, 177–187.

Gönnert, G., Müller, O., Gerkensmeier, B., 2013. Development of extreme storm surge events — results of the XtremRisK project. In: Klijn, F., Schwecckendiek, T. (Eds.), Comprehensive Flood Risk Management. Research for policy and practice.

Heaps, N.S., 1983. Storm surges, 1967–1982. Geophysical Journal of the RoyalAstronomical Society 74, 331–376.

Horsburgh KJ, Horritt M (2006) The Bristol Channel floods of 1607–reconstruction and analysis. Weather 61(10):272–277

Horsburgh, K.L., Wilson, C., 2007. Tide-surge interaction and its role in the distribution of surge residuals in the North Sea. Journal of Geophysical Research 112, CO8003.

Haigh ID, Nicholls RJ, Wells NC (2010) A comparison of the main methods for estimating probabilities of extreme still water levels. Coast Eng 57(9):838–849.

Haigh, I.D., Wijeratne, E.M.S., MacPherson, L.R., Pattiaratchi, C.B., Mason, M.S., Crompton, R.P., George, S., 2014a. Estimating present day extreme total water level exceedance probabilities around the coastline of Australia: tides, extra-tropical storm surges and mean sea level. Climate Dynamics, 42, 121-138.

Haigh, I.D., MacPherson, L.R., Mason, M.S., Wijeratne, E.M.S., Pattiaratchi, C.B., George, S., 2014b. Estimating present day extreme water level exceedance probabilities around the coastline of Australia: tropical cyclone induced storm surges. Climate Dynamics, 42, 139-147.

Harper BA (ed) (2001) Queensland climate change and community vulnerability to tropical cyclones—ocean hazards assessment stage 1—review of technical requirements. Report prepared by Systems Engineering Australia Pty Ltd in association with James Cook University Marine Modelling Unit, Queensland Govern- ment, 375 pp, March 2001.

Harper B, Hardy T, Mason L, Fryar R (2009) Developments in storm tide modelling and risk assessment in the Australian region. Nat Hazards 51:225–238.

Hunter J (2010) Estimating sea-level extremes under conditions of uncertain sea-level rise. Clim Change 99(3):331–350 Hunter J (2011) A simple technique for estimating an allowance for uncertain sea-level rise. Clim Change.

Jensen J, Müller-Navaraa S (2008) Storm Surges on the German Coast. Die Küste, Heft 74, pp. 92-125.

Jonkman SN, Kelman I (2005) Deaths during the 1953 North Sea storm surge. In: Proceedings of the solutions to coastal disasters conference. American Society for Civil Engineers, Charleston, 8–11 May, pp 749–758

Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, Dool H, Jenne R, Fiorino M (2001) The NCEP-NCAR 50-year Reanalysis: monthly Means CD ROM and documentation. Bull Am Mete- orol Soc 82(2):247–267.

Lamb H (1991) Historic storms of the North Sea, British Isles and Northwest Europe. Cambridge University Press, Cambridge

Lennon, G.W., 1963. A frequency investigation of abnormally high tidal levels at certain west coast ports. Proceedings of the Institution Civil Engineers 25, 451–484.

LKN (Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein), 2012. Generalplan Küstenschutz der Landes Schleswig-Holstein, Fortschreibung 2012. Entwurf für die Anhörung der Verbände.

Lowe JA, Woodworth PL, Knutson T, McDonald RE, McInnes K, Woth K, Von Storch H, Wolf J, Swail V, Bernier N, Gulev S, Horsburgh K, Unnikrishnan AS, Hunter J, Weisse R (2010) Past and future changes in extreme water levels and waves. In: Church JA, Woodworth PL, Aarup T, Wilson S (eds) Under- standing sea-level rise and variability. Wiley-Blackwell, Hoboken

McInnes KL, Hubbert GD (2003) A numerical modelling study of storm surges in Bass Strait. Aust Meteorol Mag 52(3):143–156

McInnes KL, Macadam I, Hubbert GD, O'Grady JD (2009) Amodelling approach for estimating the frequency of sea level extremes and the impact of climate change in southeast Australia. Nat Hazards 51:115–137.

McInnes KL, Macadam I, Hubbert GD, O'Grady JG (2011a) An assessment of current and future vulnerability to coastal inundation due to sea level extremes in Victoria, southeast Australia. Int J Clim. doi:10.1002/joc.3405.

McInnes KL, O'Grady JG, Hemer M, Macadam I, Abbs DJ, White CJ, Bennett JC, Corney SP, Holz GK, Grose MR, Gaynor SM, Bindoff NL (2011b) Climate future for Tasmania: Extreme tide and sea-level events. Technical report, Antarctic Climate and Ecosystems Corporate Research Centre.

McMillan, A., Batstone, C., Worth, D., Tawn, J. A., Horsburgh, K. & Lawless, M. 2011. Coastal flood boundary conditions for UK mainland and islands. Project: SC060064/TR2: Design sea levels.: Published by: Environment Agency, Bristol, UK.

McRobie A, Spencer T, Gerritsen H (2005) The big flood: North Sea storm surge. Philos Trans R Soc A363:1263–1270

Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas. In: Parry ML et al (eds) Climate change 2007: impacts, adaptation and vulnerability, contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cam- bridge, pp 315–356.

Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN), 2007. Generalplan Küstenschutz Niedersachsen/Bremen–Festland.

Nott J, Hayne M (2000) How high was the storm surge from tropical cyclone Mahina. Aust J Emerg Manag 15:11–13.

O'Grady JG, McInnes KL (2010) Extreme wind waves and their relationship to storm surges in northeastern Bass Strait. Aust Meteorol Oceanogr J 60:265–275.

Oumeraci, H., Burzel, A., Daemrich, K.-F., Dassanayake, D., Fröhle, P., Gerkensmeier, B., Gönnert, G., Jensen, J., Kortenhaus, A., Mudersbach, C., Naulin, M., Pasche, E., Sossidi, K., Thumm, S., Ujeyl, G., Wahl, T. (2012): Integrated Flood Risk Analysis for Extreme Storm Surges at Open Coasts and in Estuaries: Background, Methodology, Key Results

and Lessons Learned - Results of the XtremRisK Project, Proceedings of the 2nd European Conference on FLOODrisk Management, Roterdam, Netherlands, 2012.

Pugh, D.J., Vassie, J.M., 1979. Extreme sea-levels from tide and surge probability. Proceedings of the Sixteenth Coastal Engineering Conference, Hamburg, German, 27 Aug–3 Sep 1978. American Society of Civil Engineers. New York 1, 911–930.

Pugh, D.J., Vassie, J.M., 1980. Applications of the joint probability method for extreme sea-level computations. Proceedings of the Institution of Civil Engineers Part 2 (69), 959–975.

Pugh DT (2004) Changing sea levels: effects of tides, weather and climate. Cambridge University Press, Cambridge.

RMS (2003) December 1703 Windstorm, 300-year retrospective. Risk Management Solutions Report.
http://www.rms.com/Publications/1703_Windstorm.pdf

RMS (2007) 1607 Bristol Channel Floods: 400-year retrospective. Risk Management Solutions Report.
http://rms.com/Publications/1607_Bristol_Flood.pdf

Rossiter JR (1954) The North Sea surge of 31 January and 1 February 1953. Phil Trans R Soc Lond A246: 371–400

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Editors: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner GK, Allen SK, Tignor M, Midgley PM. A Special Report of Working Groups I and II of the Intergov- ernmental Panel on Climate Change (IPCC). Cambridge Uni- versity Press, Cambridge, UK, and New York, NY, USA, pp 109–230.

Suthons, C.T., 1963. Frequency of occurrence of abnormally high sea levels on the east and south coasts of England. Proceedings of the Institution of Civil Engineers 25, 433–450.

Swift, R., 2003. Extreme water levels — an interregional comparison. ABPmer Internal Report Number R1058.

Uppala SM, Ka˚llberg PW, Simmons AJ, Andrae U, da Costa Bechtold V, Fiorino M, Gibson JK, Haseler J, Hernandez A, Kelly GA, Li X, Onogi K, Saarinen S, Sokka N, Allan RP, Andersson E, Arpe K, Balmaseda MA, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Caires S, Chevallier F, Dethof A, Dragosavac M, Fisher M, Fuentes M, Hagemann S, Ho´lm E, Hoskins BJ, Isaksen L, Janssen PAEM, Jenne R, McNally AP, Mahfouf J-F, Morcrette J–J, Rayner NA, Saunders RW, Simon P, Sterl A, Trenberth KE, Untch A, Vasiljevic D, Viterbo P, Woollen J (2005) The ERA-40 re-analysis. Q J R Meteorol Soc 131:2961–3012. doi:10.1256/qj.04.176

Verlaan M, Zijderveld A, Vries HD, Kross J (2005) Operational storm surge forecasting in the Netherlands: developments in the last decade. Phil Trans R Soc Lond A363(1831):1441–1453

Von Storch H, Woth K (2006) Storm surges—the case of Hamburg, Germany. ESSP OSC panel session on ‘‘GEC, natural disasters, and their implications for human security in coastal urban areas’’. Available online: http://www.safecoast.nl/editor/databank/File/hamburg-storms.pdf. Accessed 26 Jan 2012

Wahl, T., Mudersbach, C., Jensen J. (2011): Assessing the hydrodynamic boundary conditions for risk analyses in coastal areas: A stochastic storm surge model, Nat. Hazards Earth Syst. Sci. 11, 2925-2939, doi:10.5194/nhess-11-2925-2011.

Wahl T, Mudersbach C, Jensen J (2012) Assessing the hydrodynamic boundary conditions for risk analyses in coastal areas: A multivariate statistical approach based on Copula functions, Nat. Hazards Earth Syst. Sci., Nat. Hazards Earth Syst. Sci., 12, 495-510, doi:10.5194/nhess-12-495-2012.

Zhang K, Douglas BC, Leatherman SP (1997) East coast storm surges provide unique climate record. EOS Trans Am Geophys Union 78(37):389–397.

Zhang K, Douglas BC, Leatherman SP (2000) Twentieth-century storm activity along the US east coast. J Clim 13:1748–1761.

Figure 1: One in 100-year sea-level around the UK. Values are shown in meters above Ordnance Datum Newlyn. Source – Badstone et al. (2013).

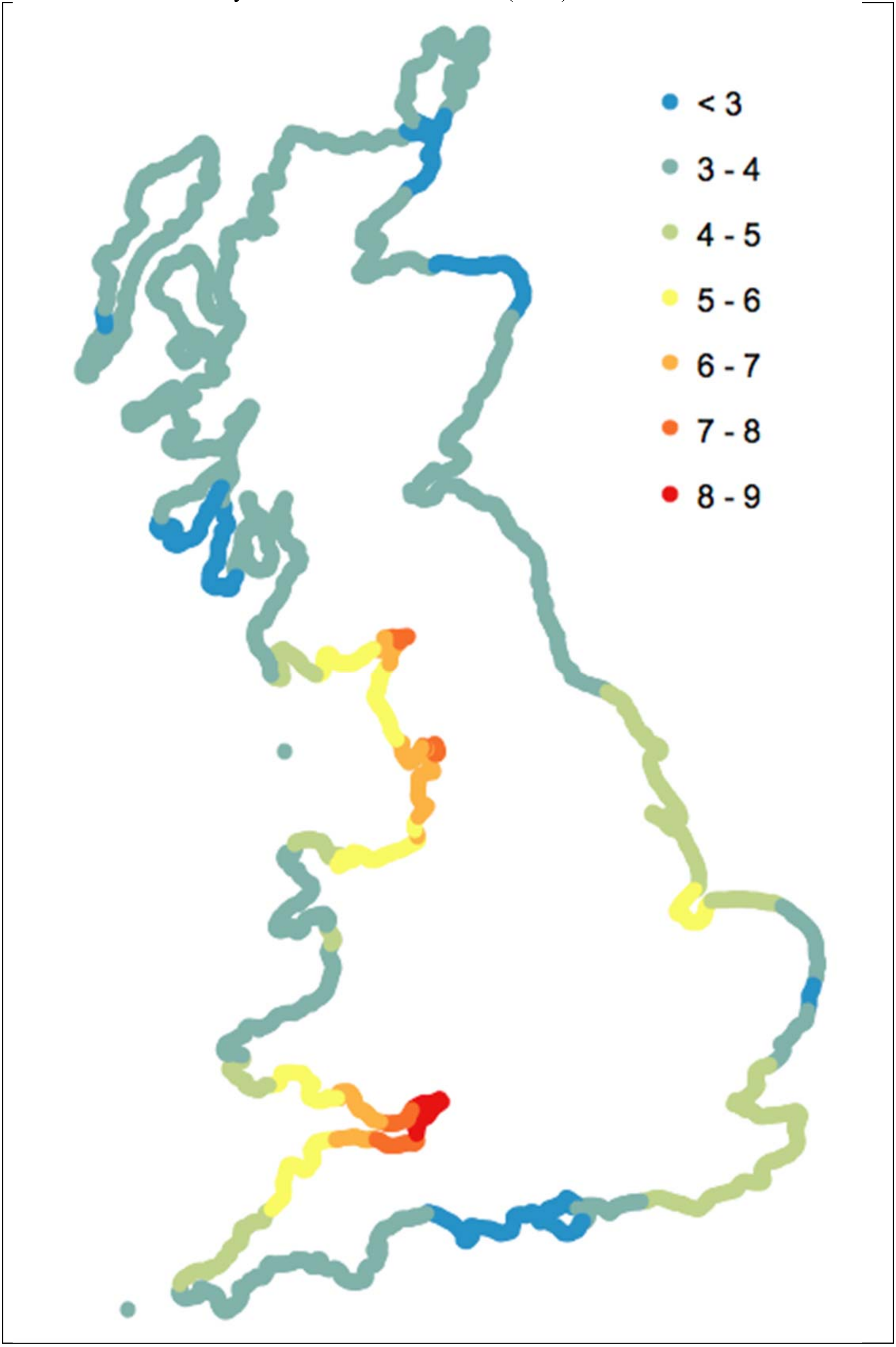


Figure 2: The 16 federal states of Germany (depicted in dark grey). The four federal states being exposed to North Sea tides are shown in different colours according to the legend. Source – Arns et al. (2013).

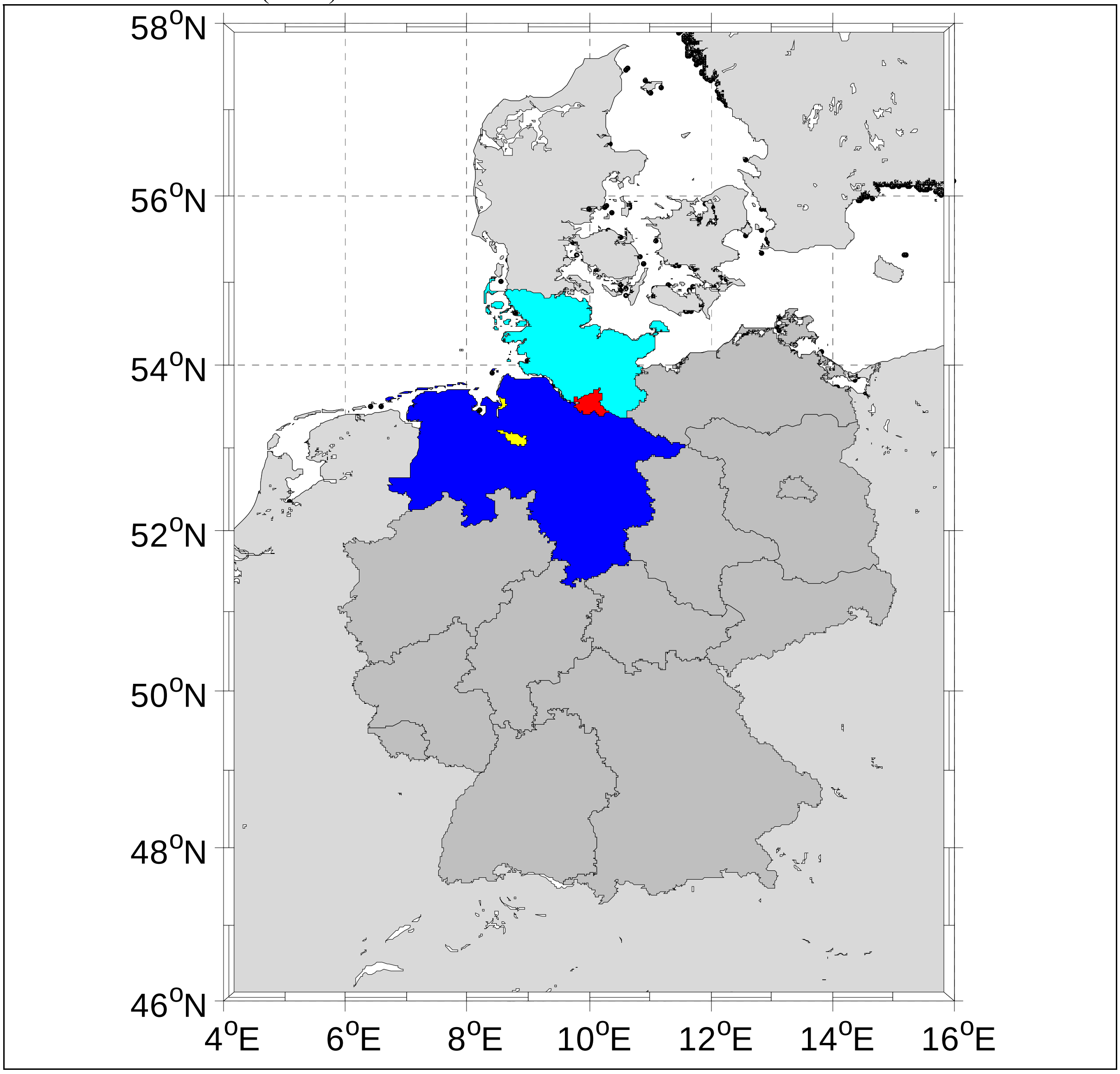


Figure 3: 200-yar return water levels at all model grid points along the entire coastline of Schleswig-Holstein (a) and the small island (German: Hallig) Nordstrandischmoor (b). Source Arns et al. (2014).

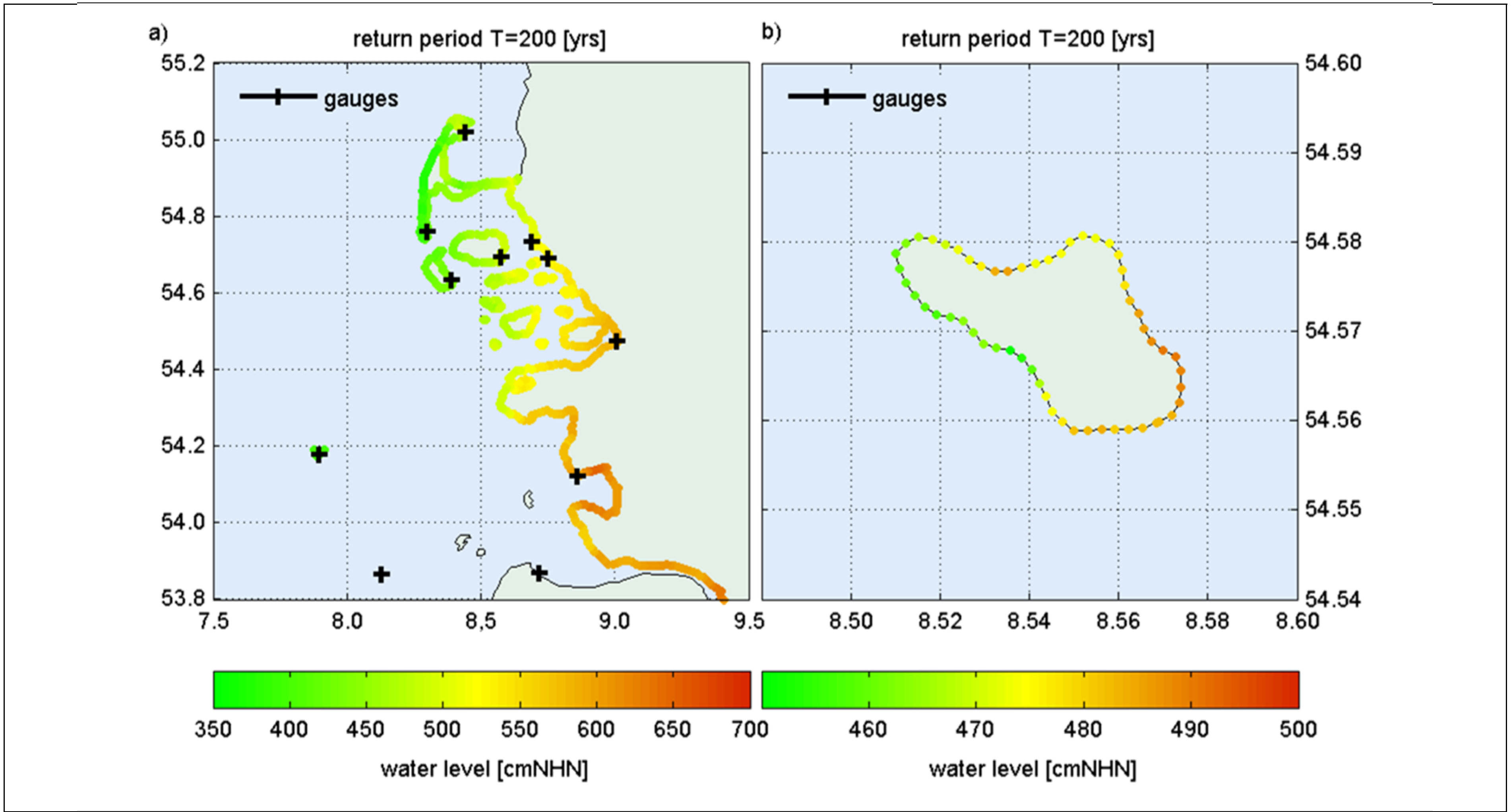


Figure 4: Hydrodynamic model grid and bathymetry configured in Mike21 FM and the 30 validation tide gauge sites. Source – Haigh et al. (2014b).

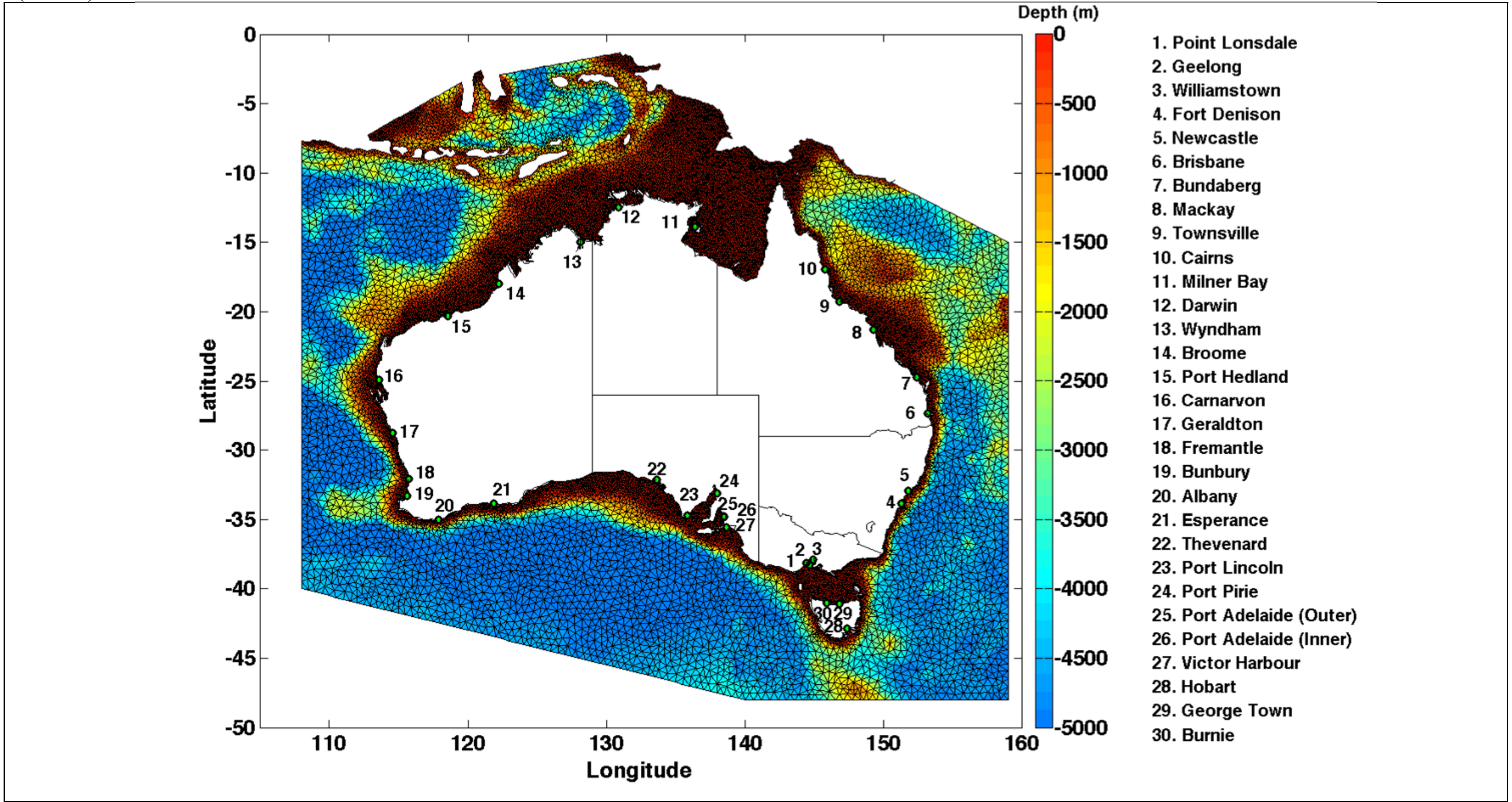
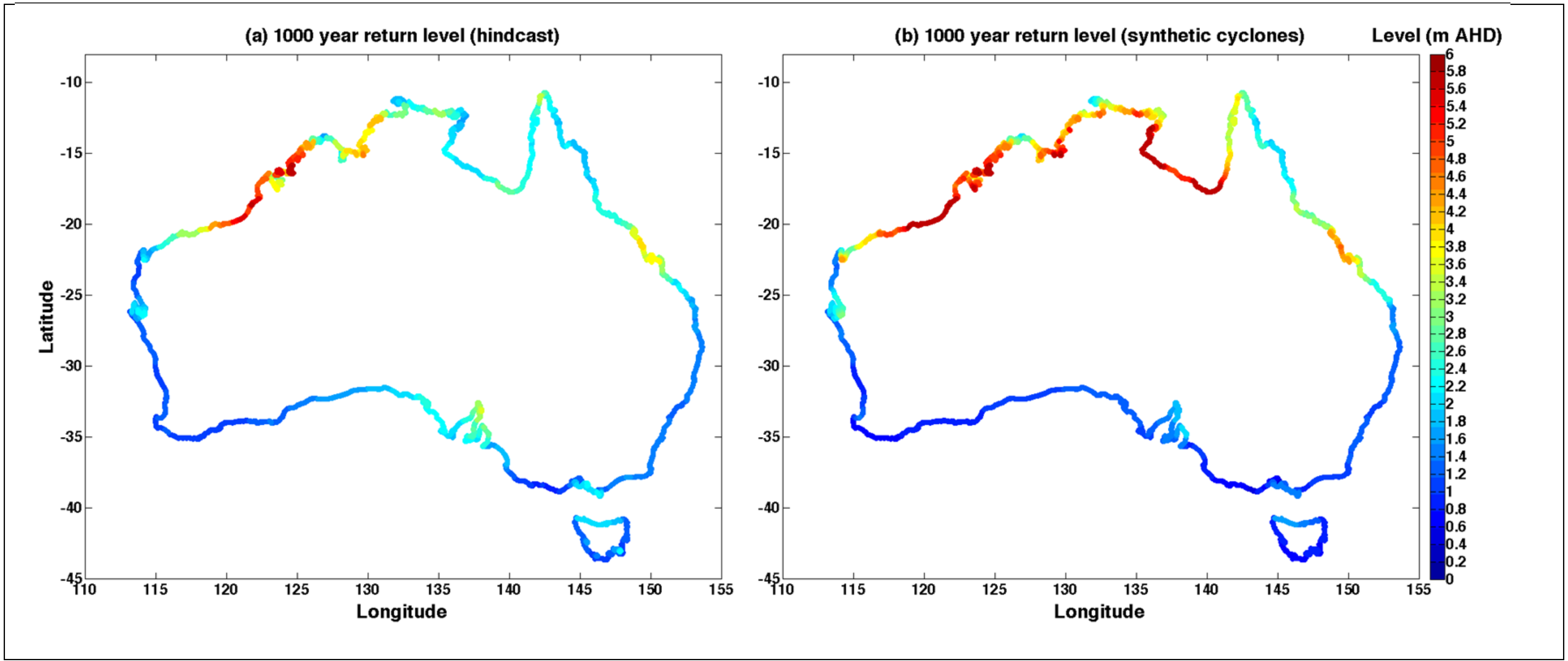


Figure 5: 1,000-year surge return levels for 2010 (relative to AHD) at the model coastal grid points estimated using data from (a) the 61-year hindcast and (b) the simulations run using forcing from the 10,000 year synthetic tropical cyclone data set described in this current paper. Note: the return levels in (a) are derived considering both extra-tropical and tropical cyclones, although the tropical cyclones induced surges are under-estimated because of the relatively coarse meteorological forcing used in the hindcast.



Application of a Multivariate Extreme Value Method for Spatially Coherent Coastal Flood Risk Analysis

Ben Gouldby HR Wallingford

19th February 2014

USACE Extreme Sea Level Workshop

Introduction

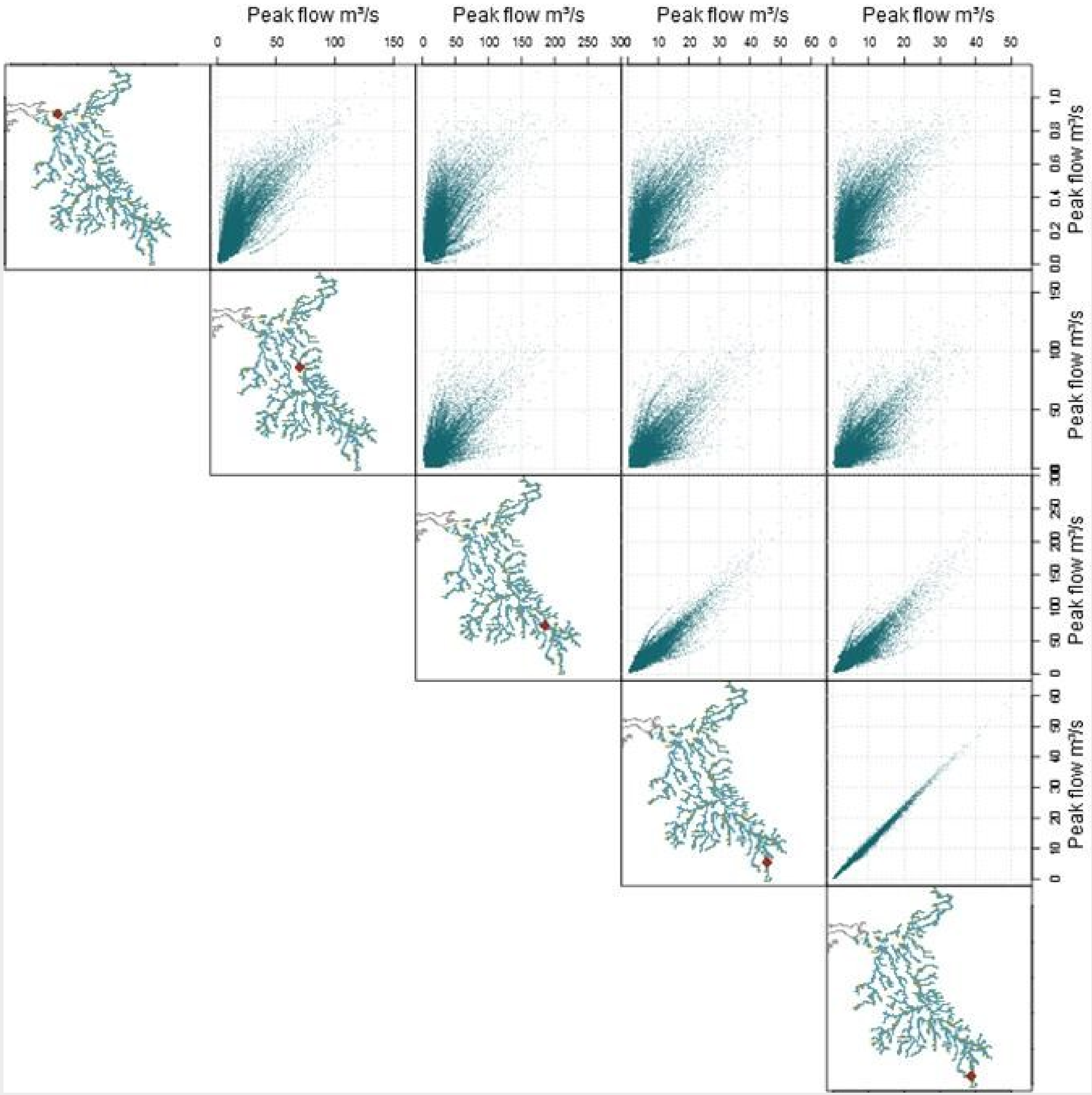
- Background to the problem
- Multivariate method
- Application at small spatial scale (Northern Spain)
- On-going application at larger spatial scale to East Coast Surges

Background

- Flooding can arise over large spatial scales where its severity is not constant
- Need to model spatial dependence in the extremes:
  - To assess risk for insurance, for example
  - Emergency planning

Shoothill flood alerts

Background



Peak flow m³/s
Peak flow m³/s
Peak flow m³/s
Peak flow m³/s
0 50 100 150
0 50 100 150 200 250 300
10 20 30 40 50 60
0 10 20 30 40 50
0.0 0.2 0.4 0.6 0.8 1.0
0 50 100 150
0 50 100 150 200 250 300
0 10 20 30 40 50 60

The Heffernan and Tawn (2004) method

- Copula-based (i.e. separates marginal extremes)
- Works with any number of extreme variables (could potentially extend to different sources, river flow/sea level, sea level and waves, sea level/rainfall etc., clustering)

Heffernan, J. E. and Tawn, J. A. (2004). *A conditional approach for multivariate extreme values (with discussion).* Journal of the Royal Statistical Society, Series B (Statistical Methodology) 66 (3): 497–546.

Marginal Extremes

First fit extremes to each margin

Generalised Pareto Distribution (GPD):

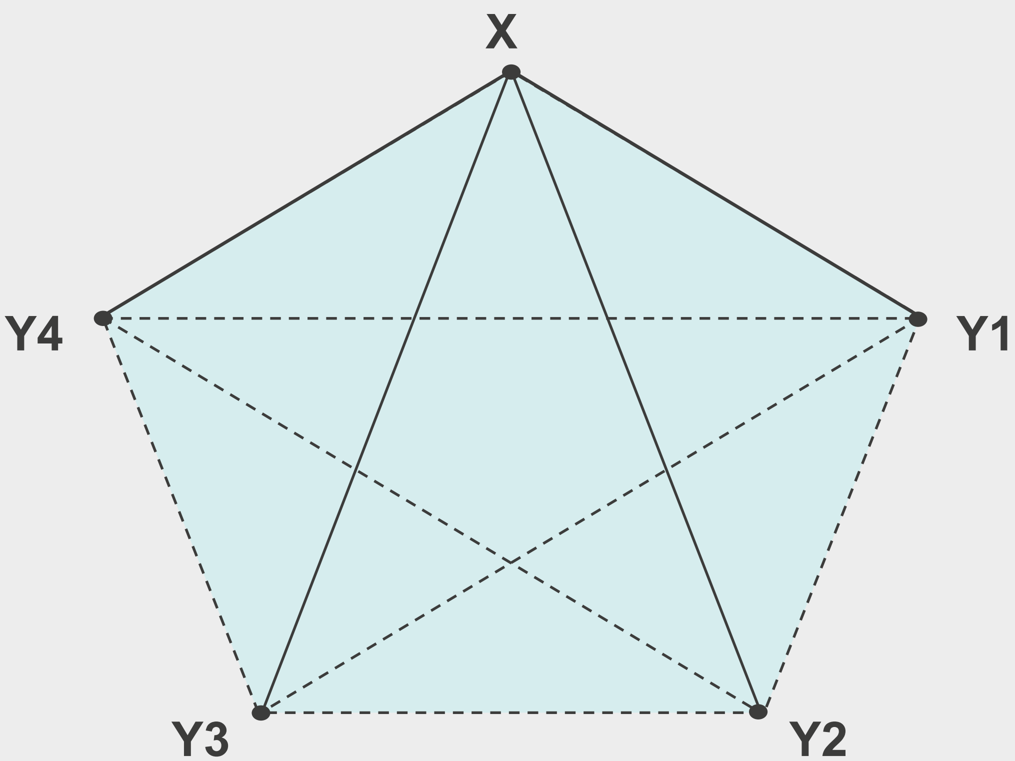
$$\mathrm{P}(X_i > x \mid X_i > u_i) = \left[1 + \xi_i \frac{(x - u_i)}{\beta_i}\right]_+^{-1/\xi_i}$$

Empirical distribution below the threshold

Regression Model

For each pair of variables a non-linear regression model is fitted:

$$Y_j \mid Y_i = a_{j|i}\, Y_i + Y_i^{\,b_{j|i}}\, Z_{j|i} \qquad \text{for } Y_i > v$$

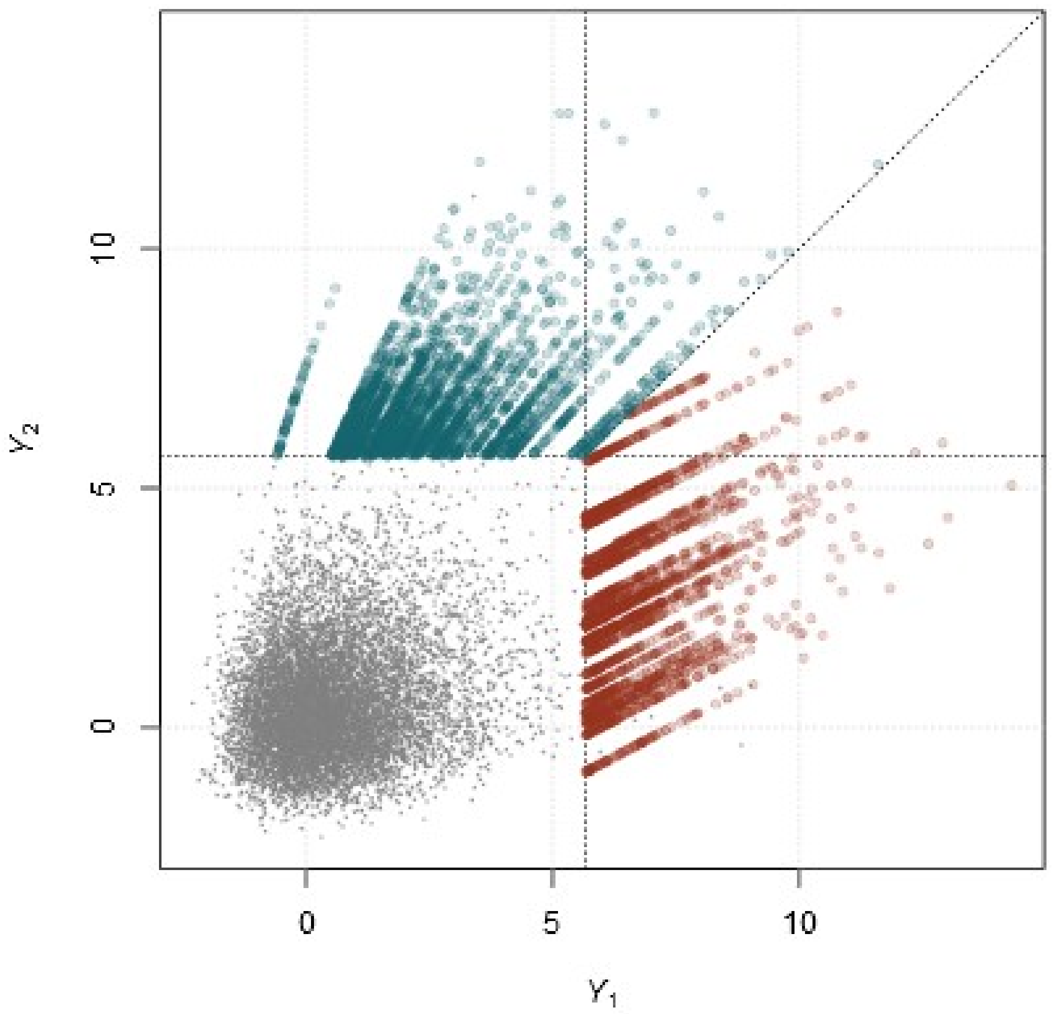


From EA (2011) Risk of widespread flooding SC060088/R1 Spatial Coherence of Flood Risk

Simulation of Extreme Events

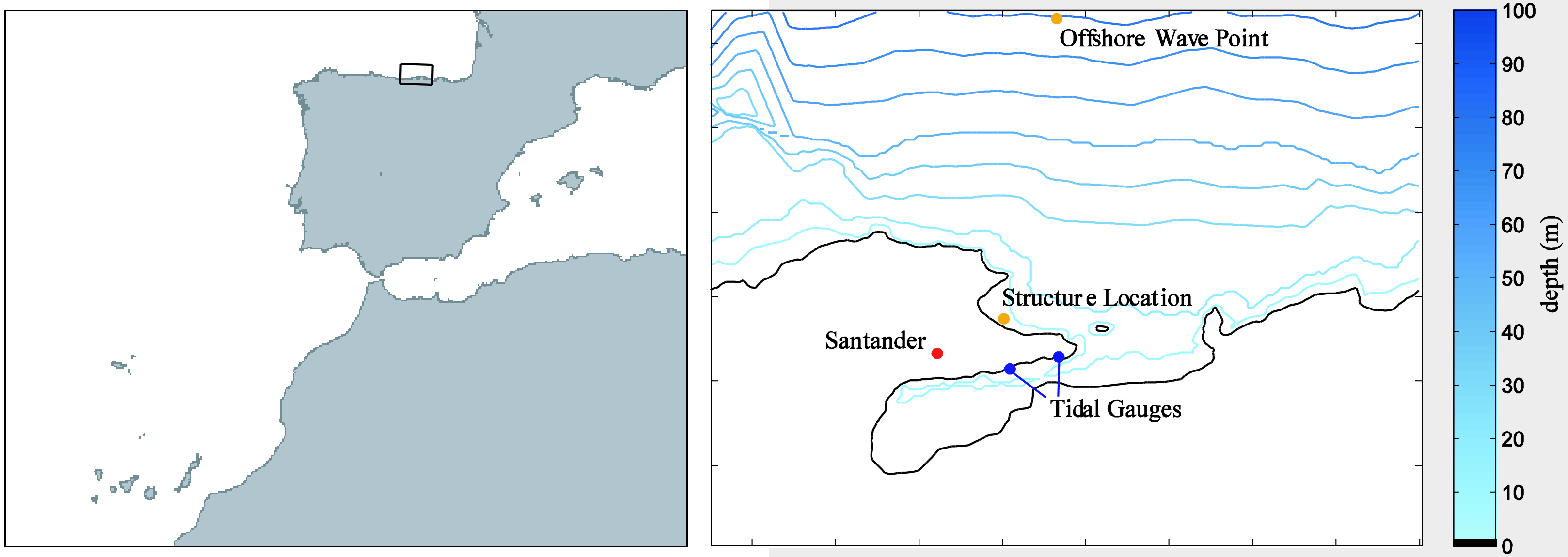
For extreme variable i:

1. Sample Y_i on transformed scales
2. Randomly select joint residual $\boldsymbol{Z}_i$
3. For each j set
$$Y_j = a_{j|i}\, Y_i + Y_i^{b_{j|i}}\, Z_{j|i}$$
4. Reject $\boldsymbol{Y}$ unless Y_i largest
5. Transform back to original scale



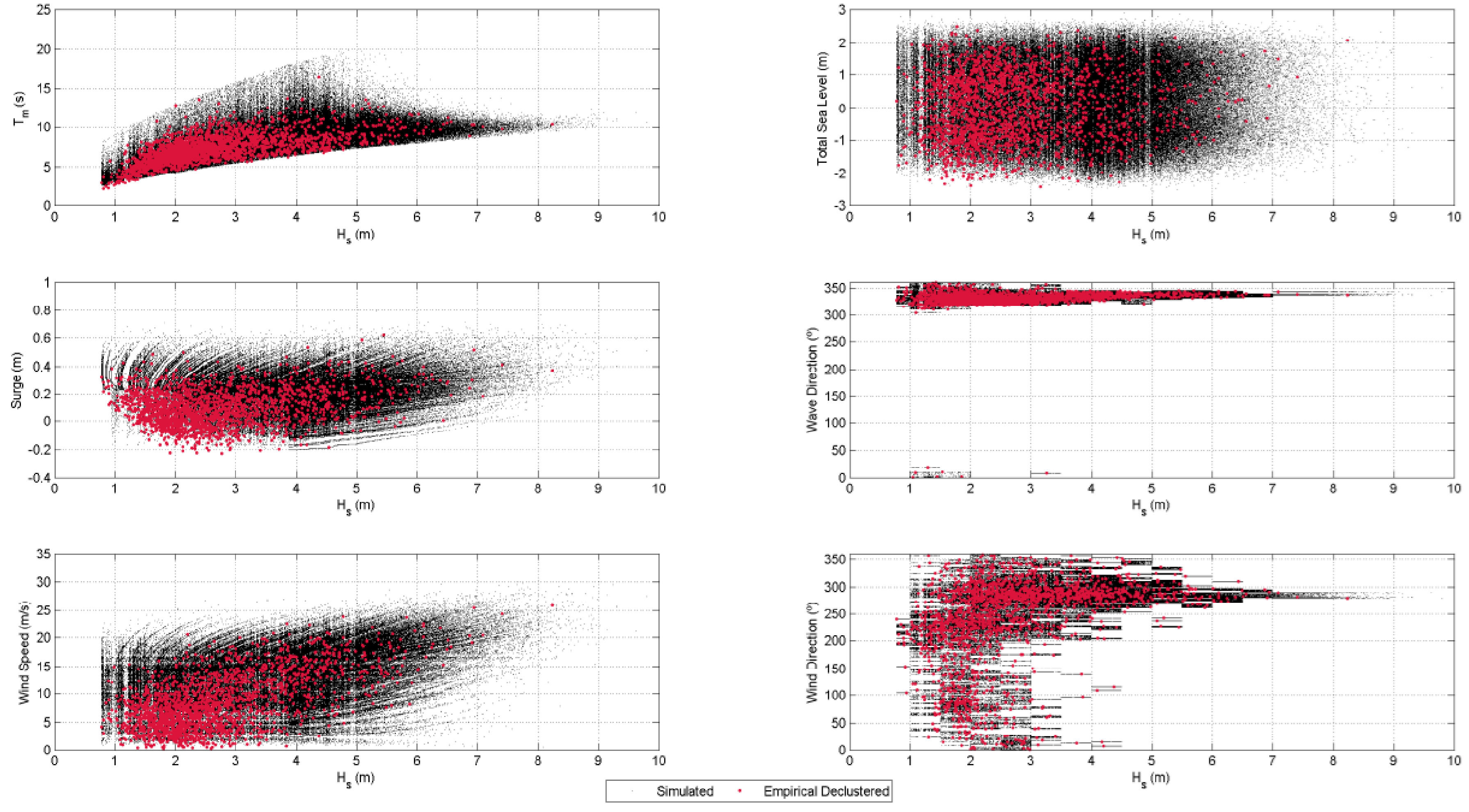
Case studies

Santander – wave transformation

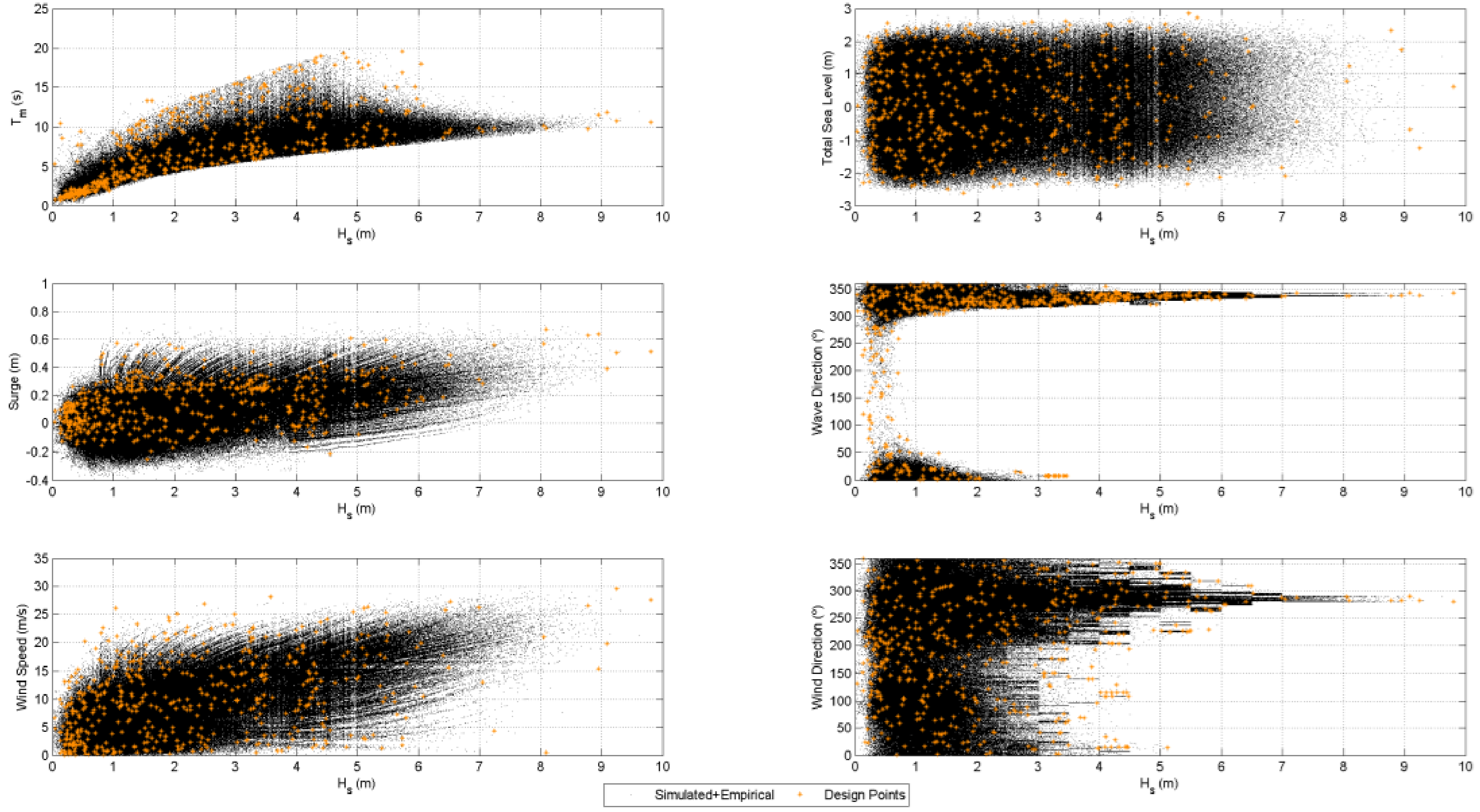


Variable	Statistical treatment for simulation
Significant Wave Height (Hs)	HT04
Wave Period (Tm)	$f(H_s, st)$
Wave Steepness (st)	Regression, conditional on H_s
Surge level (S)	HT04
Wind Speed (U)	HT04
Wind Direction (θ_U)	Empirical distribution
Wave Direction (θ_{Hs})	Empirical Distribution
Tide level (AT)	"Empirical" distribution, conditional on S and month

Offshore –empirical and simulated data

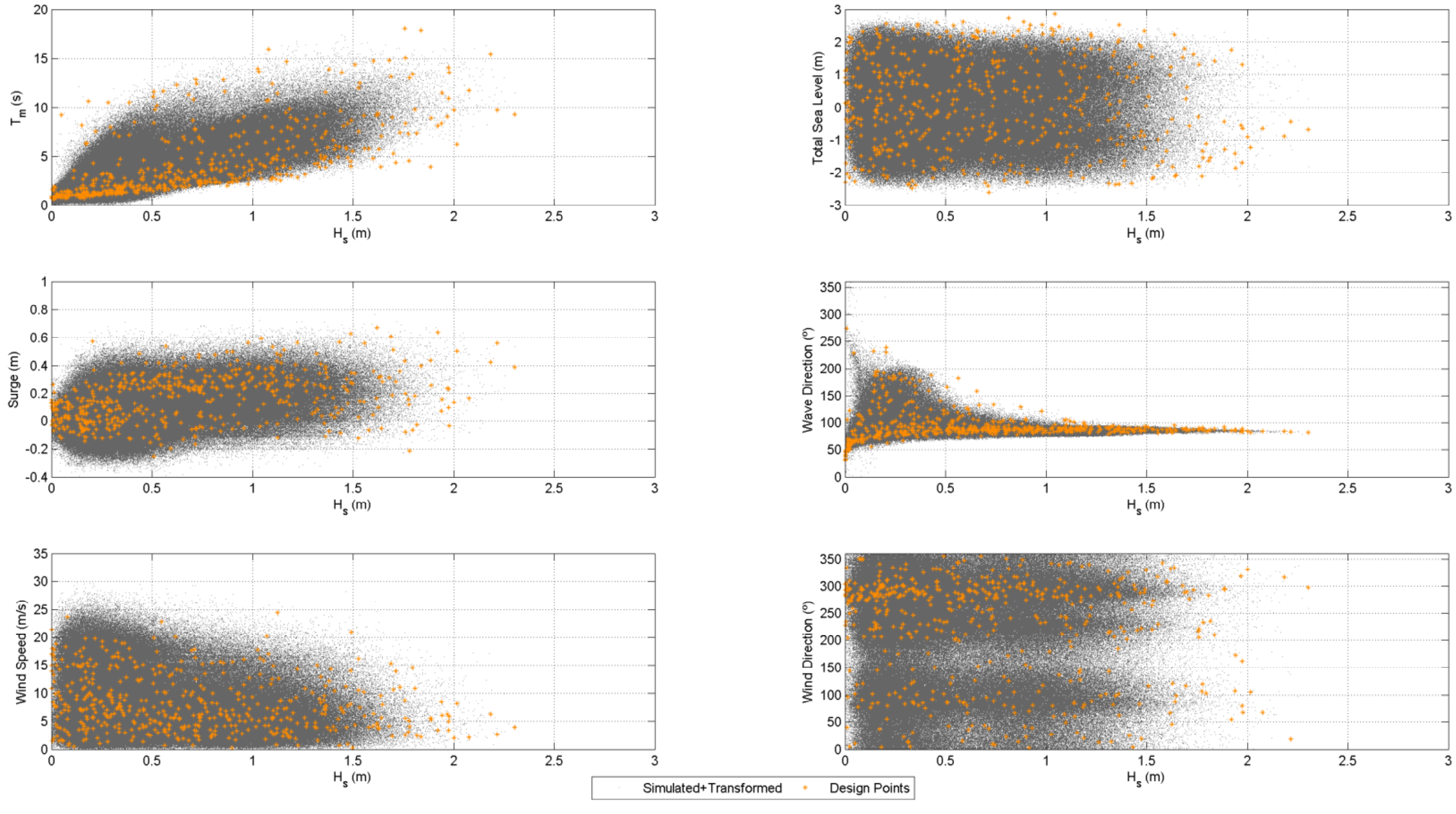


Defining the design points

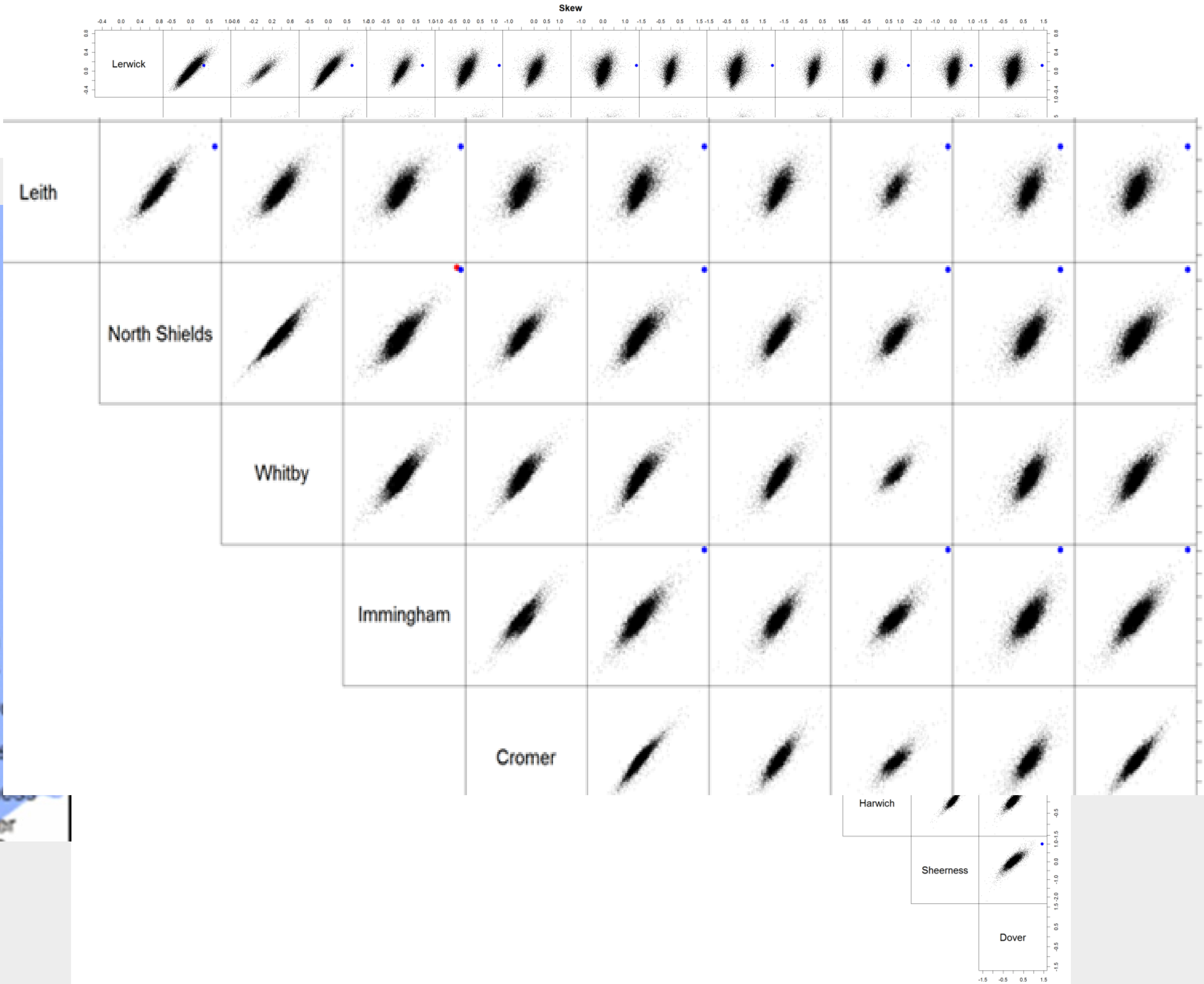


IH Cantabria method - Camus, P., Mendez, F.J. and Medina, R., 2011a. A hybrid efficient method to downscale wave climate to coastal areas. Coastal Engineering, 58(9): 851-862.

Near-shore results




Wick
Aberdeen
Leith
North Shields
Whitby
Heysham
Immingham
Liverpool
Cromer
Newport
Avonmouth
Dover


Skew
Lerwick
Leith
North Shields
Whitby
Immingham
Cromer
Harwich
Sheerness
Dover

Future application

- Flooding can arise over large spatial scales where its severity is not constant
- Need to model spatial dependence in the extremes:
  - To assess risk for insurance, for example
  - Emergency planning

Acknowledgments

IH Cantabria:

Fernando Mendez, Yanira Guanche, Ana Rueda, Roberto Minguez

HR Wallingford:

David Wyncoll, Dominic Hames

Questions

?

HR Wallingford
Working with water

Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom

1330 Avenue of the Americas Suite 23A, New York, NY 10019, USA

2800 Post Oak Boulevard Suite 4100, Houston, TX 77056, USA

www.hrwallingford.com

HR Wallingford
Working with water

Extreme Sea Level Analysis in the UK

USACE Extreme Sea Level Workshop

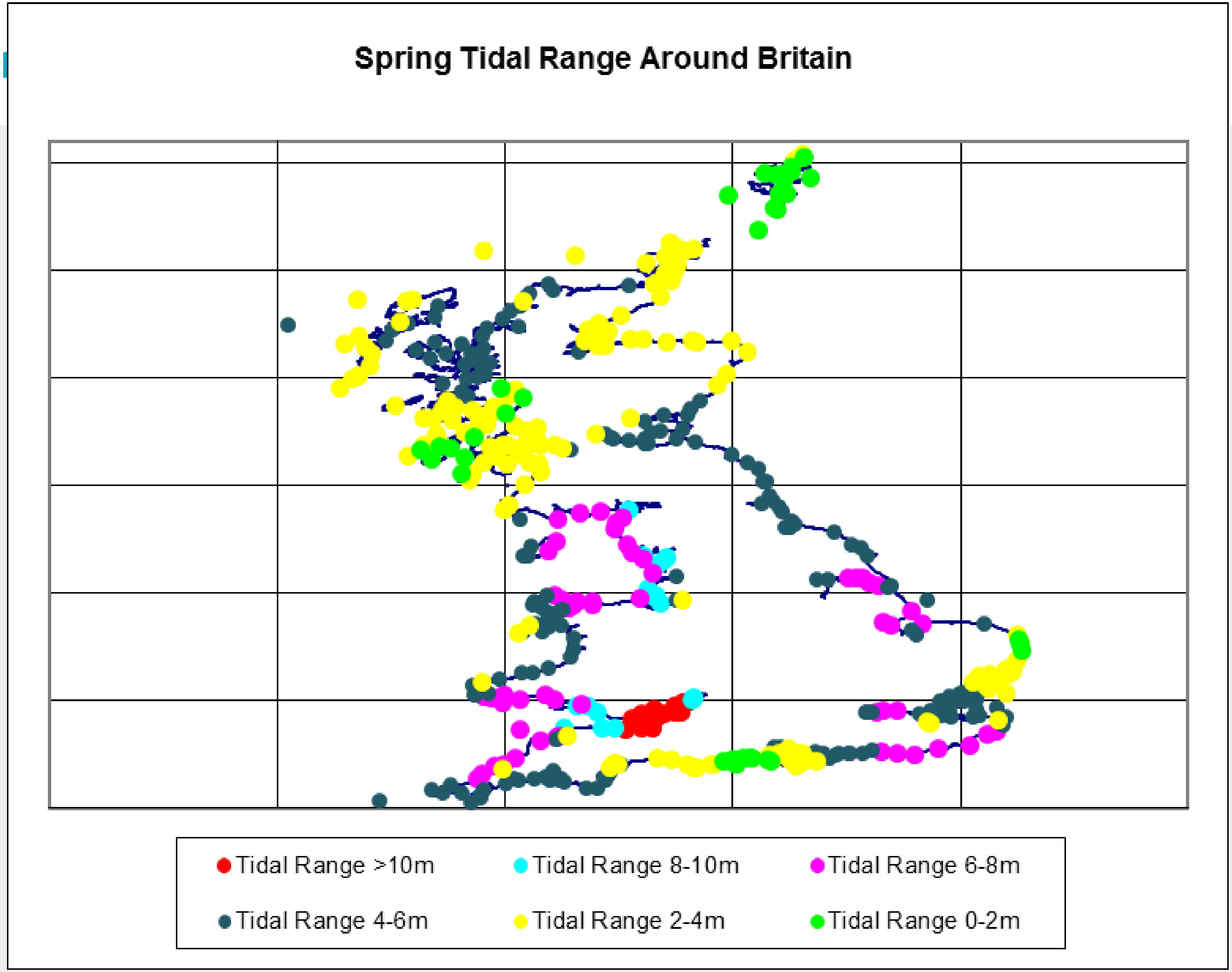
18th February 2014

Ben Gouldby

Overview of Presentation

- Setting the scene
  - Tidal range
  - “A Class” measuring stations
  - East Coast surges
- Historic analyses
- Latest analysis
- Climate change
  - Sea level rise
  - Storminess (surges and waves)
- Summary

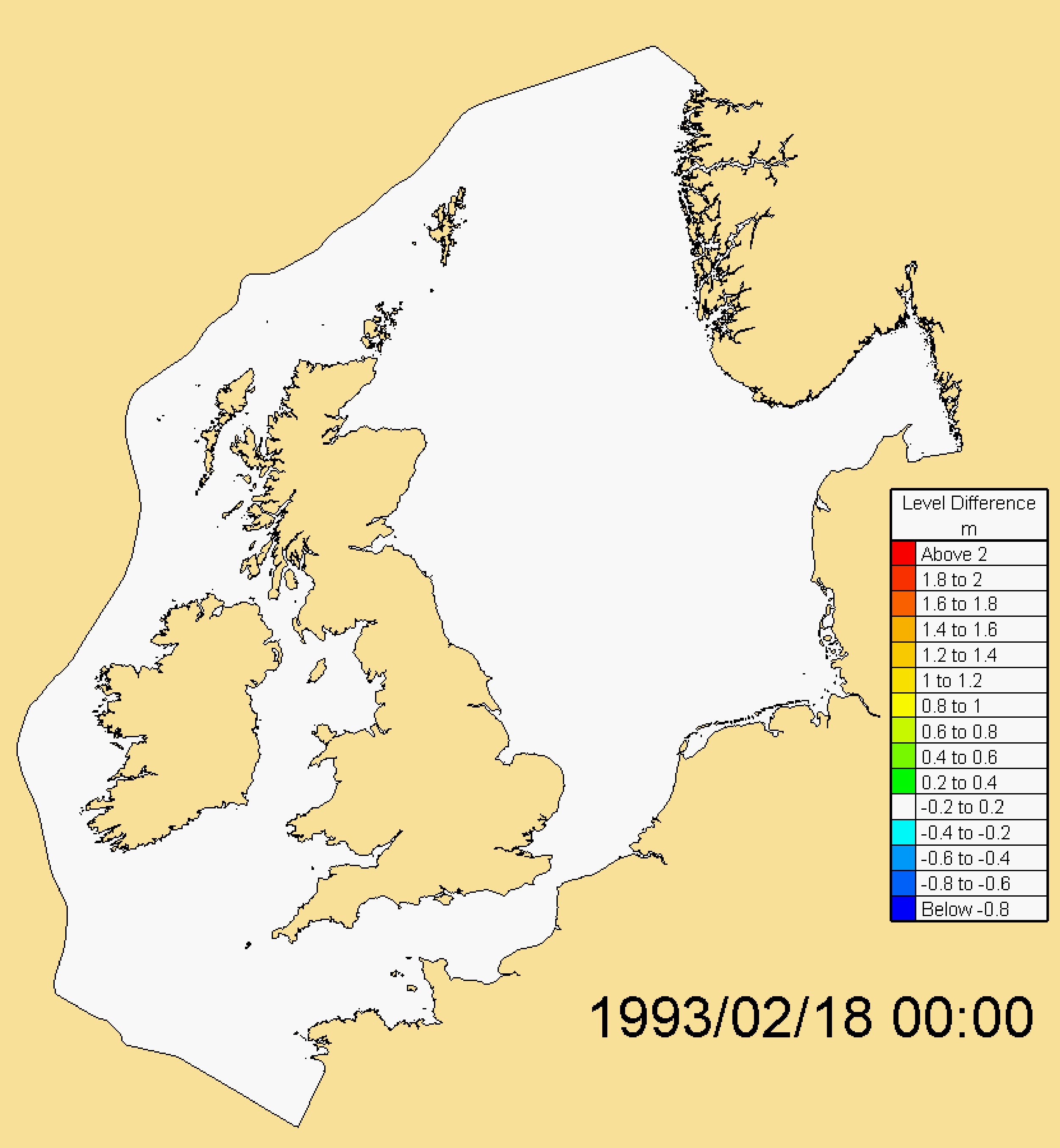
Tidal range


Spring Tidal Range Around Britain
Tidal Range >10m
Tidal Range 8-10m
Tidal Range 6-8m
Tidal Range 4-6m
Tidal Range 2-4m
Tidal Range 0-2m

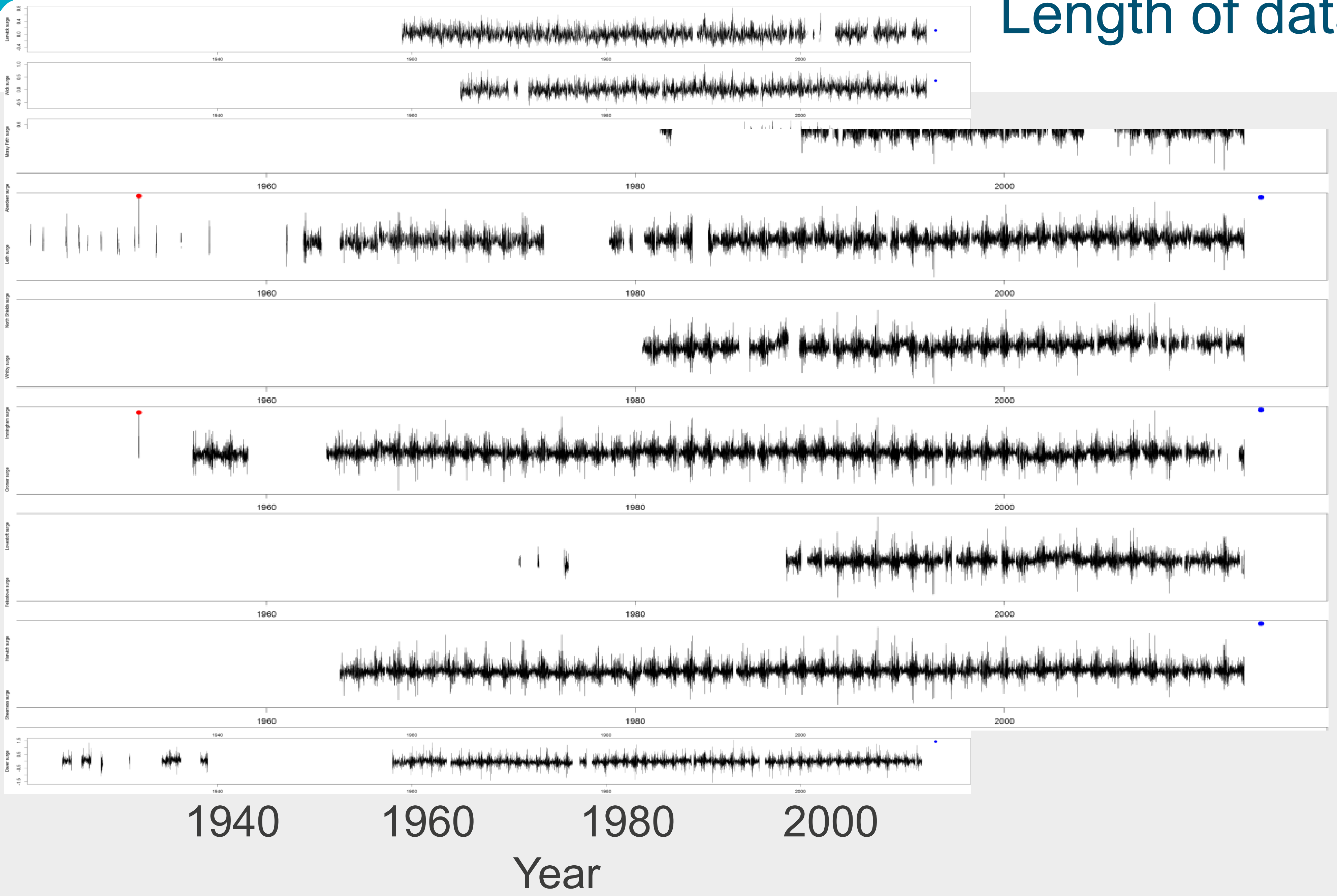
HR Wallingford
Working with water

Courtesy of Kevin Horsburgh National Oceanography Centre (NOC)

1993 East Coast surge



Length of data



A bit of history

Graf J (1981) – GEV fit to annual maxima at the tide gauge locations

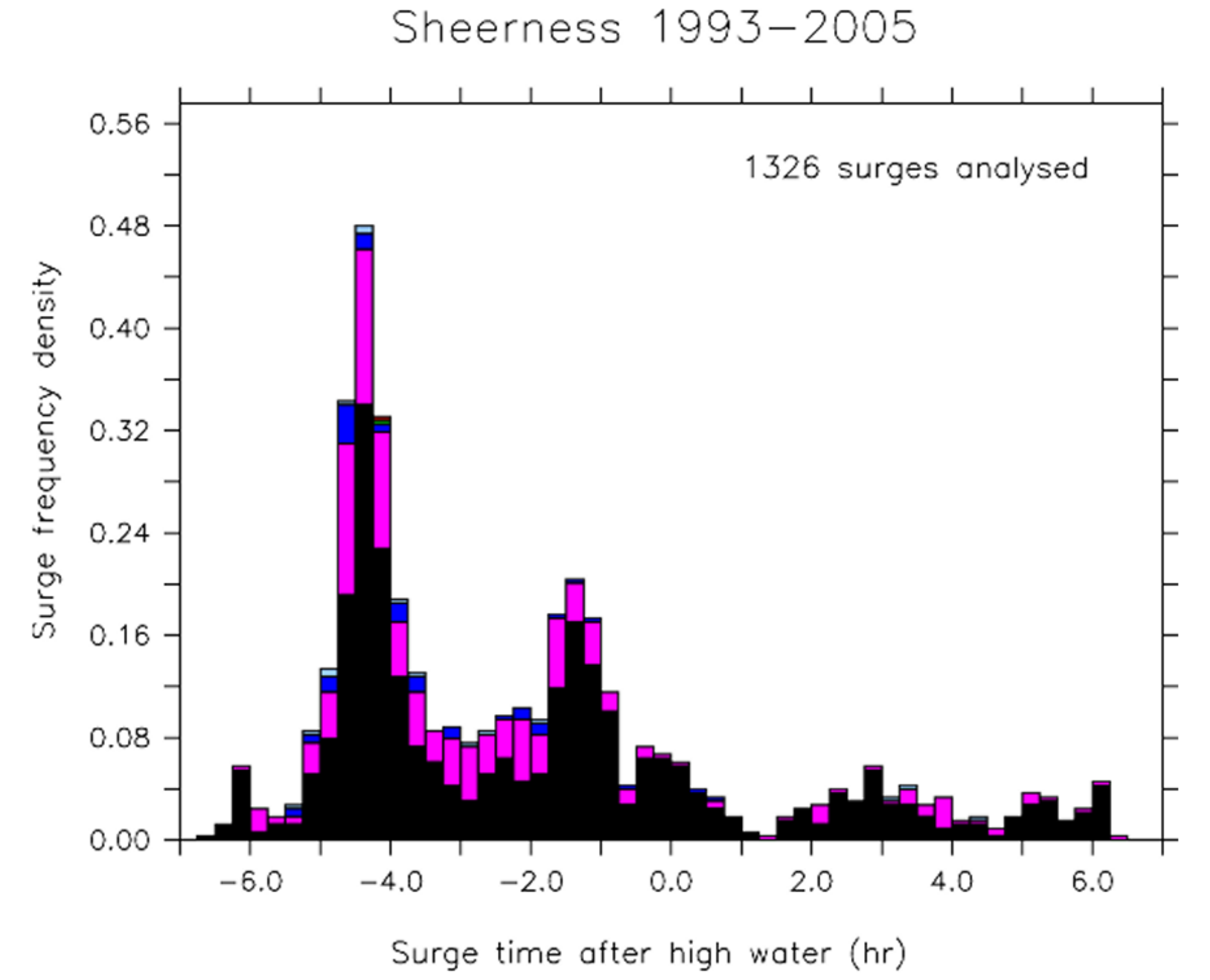
Dixon, M.J., Tawn, J.A. (1994) “r” largest method at the tide gauge locations – separate tide surge analysis

Dixon, M.J., Tawn, J.A. (1995) refined “r” largest method at the tide gauge locations and spatial analysis for the East coast using numerical model – separate tide surge analysis

Dixon, M.J., Tawn, J.A. (1997) refined “r” largest method at the tide gauge locations and spatial analysis for the UK using a numerical model – separate tide/surge analysis

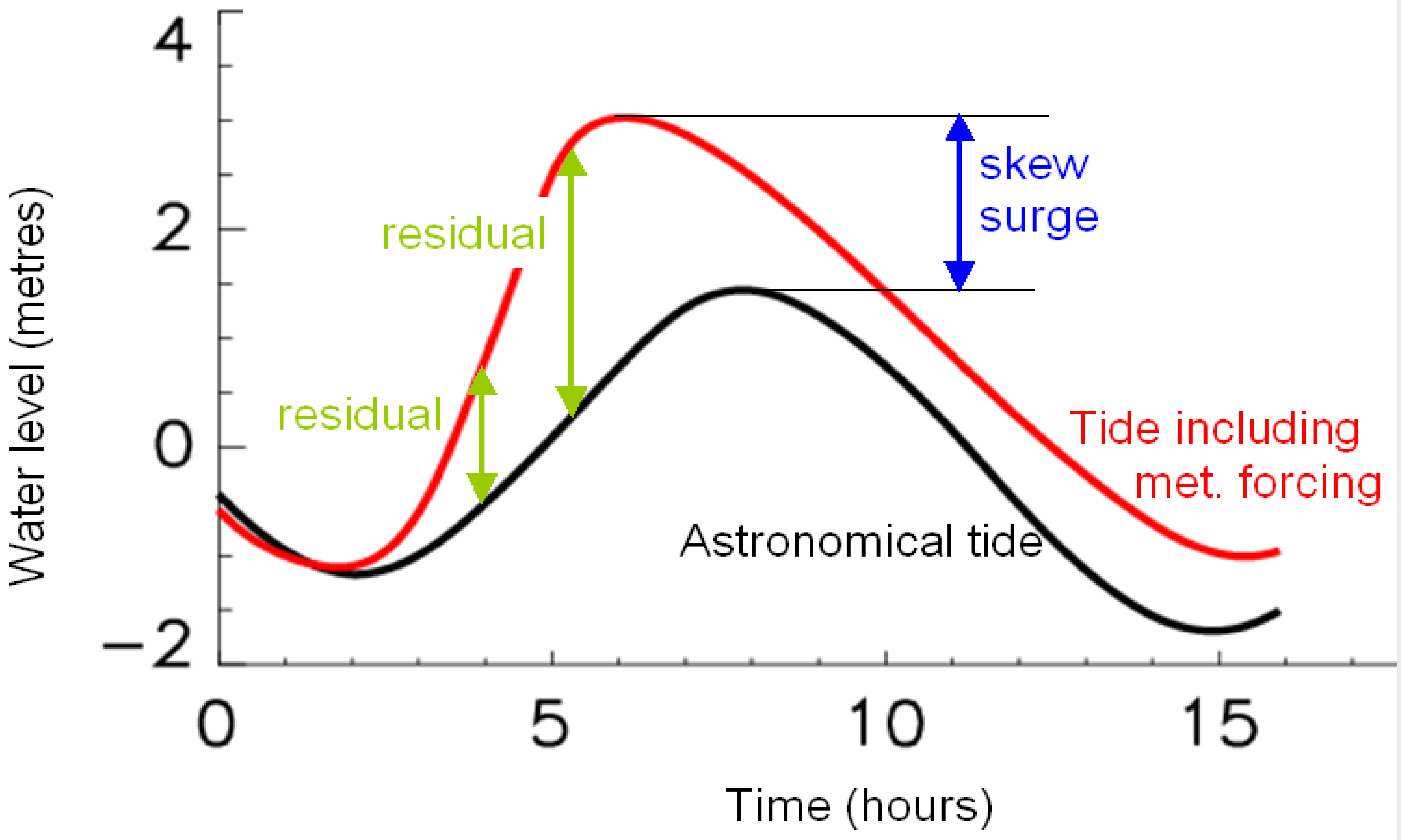
Environment Agency (2011) GPD fit to data at tide gauge locations, spatial analysis using numerical model – introduction of skew surge

Tide/surge interaction



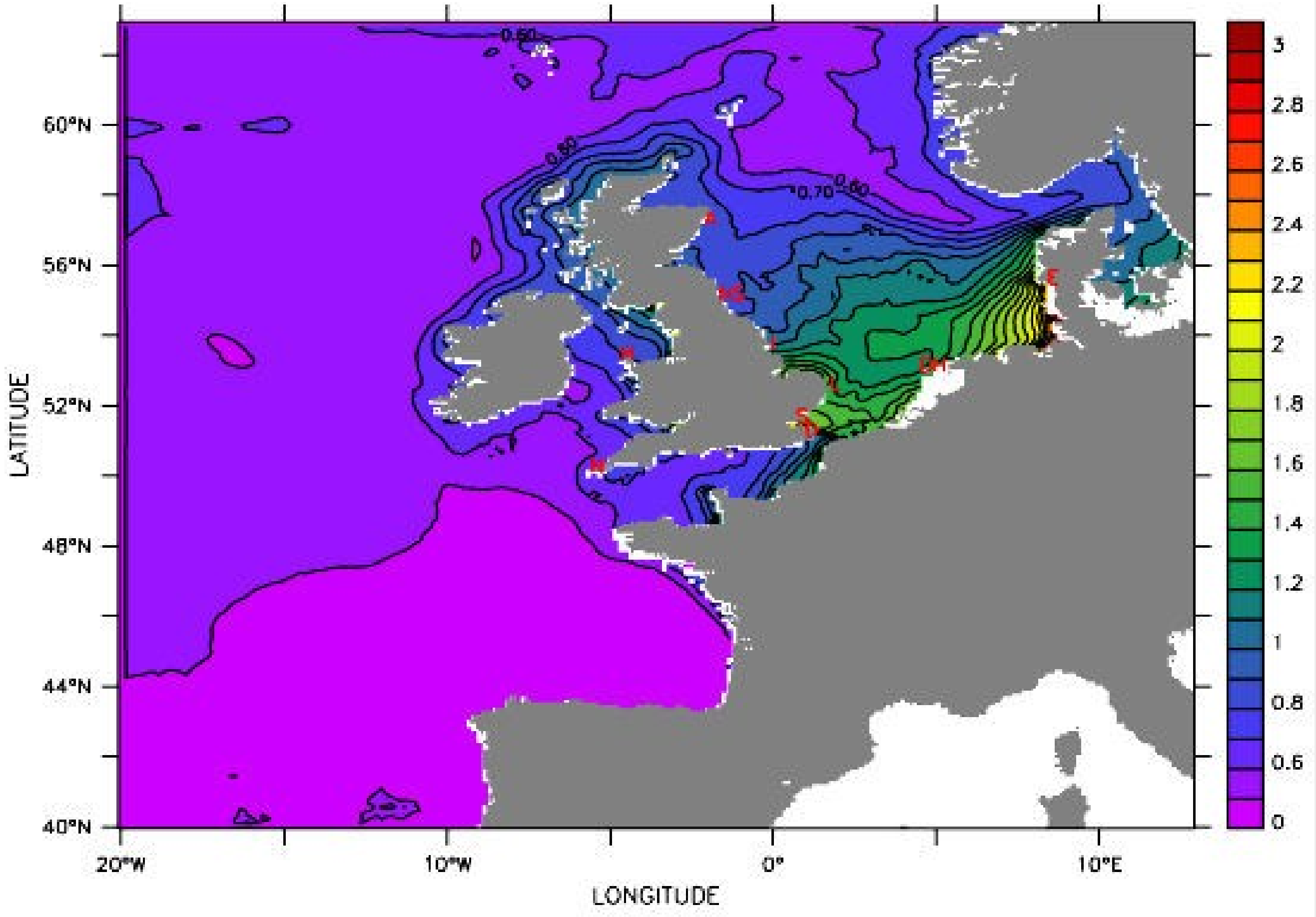
Courtesy of Kevin Horsburgh National Oceanography Centre (NOC)

Skew surge



Courtesy of Kevin Horsburgh National Oceanography Centre (NOC)

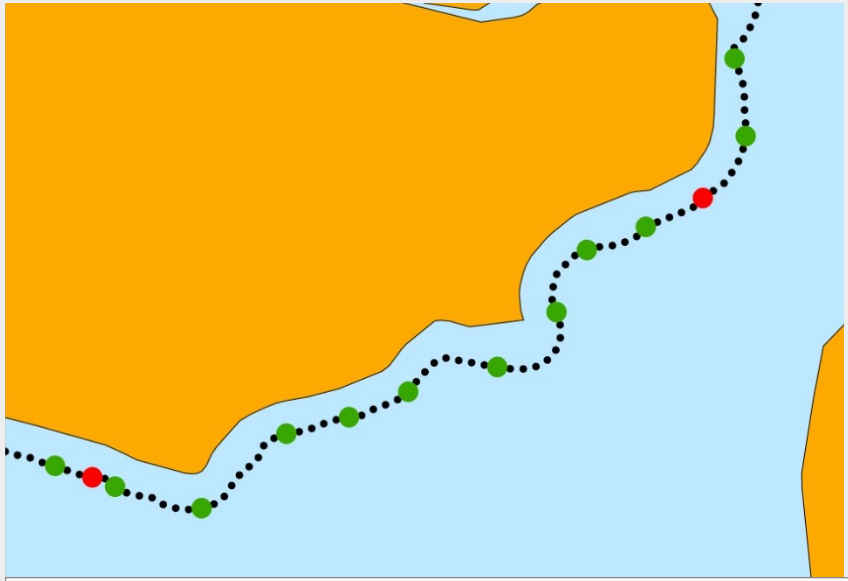
Spatial interpolation

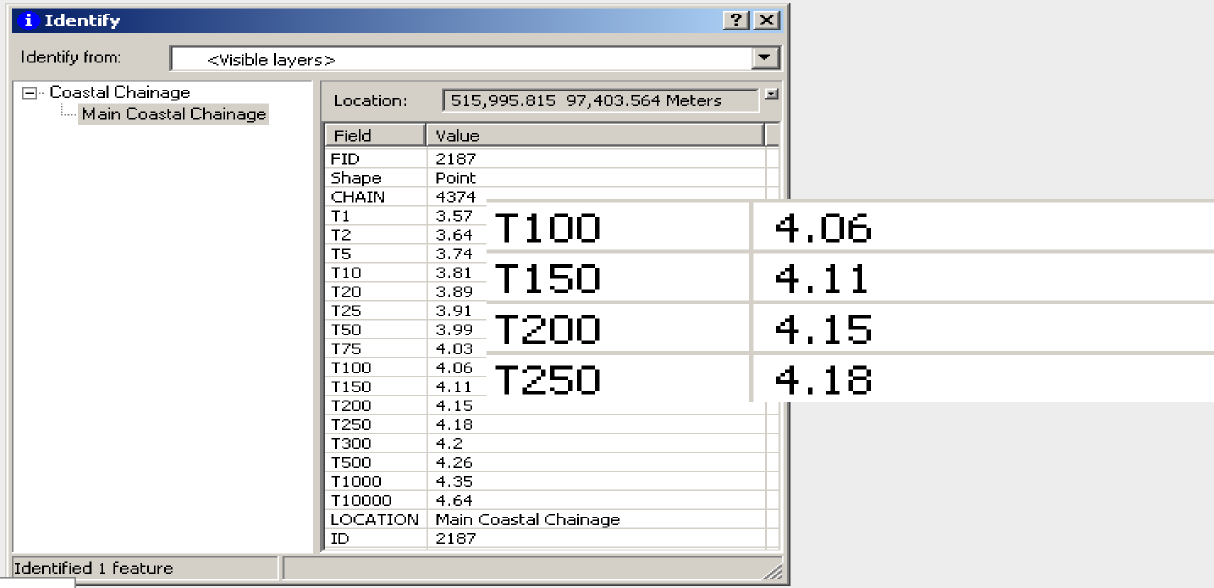


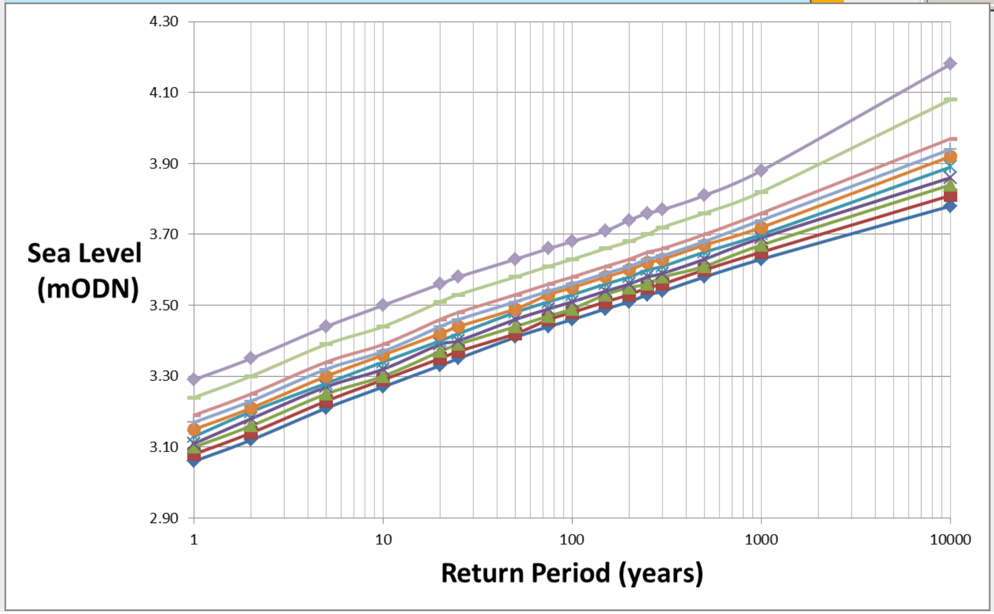
POL operational tide-surge model at 12 km resolution to dynamically interpolate between the estimates of extreme water levels at tide gauge sites

Courtesy of Kevin Horsburgh National Oceanography Centre (NOC)

Spatial database for results







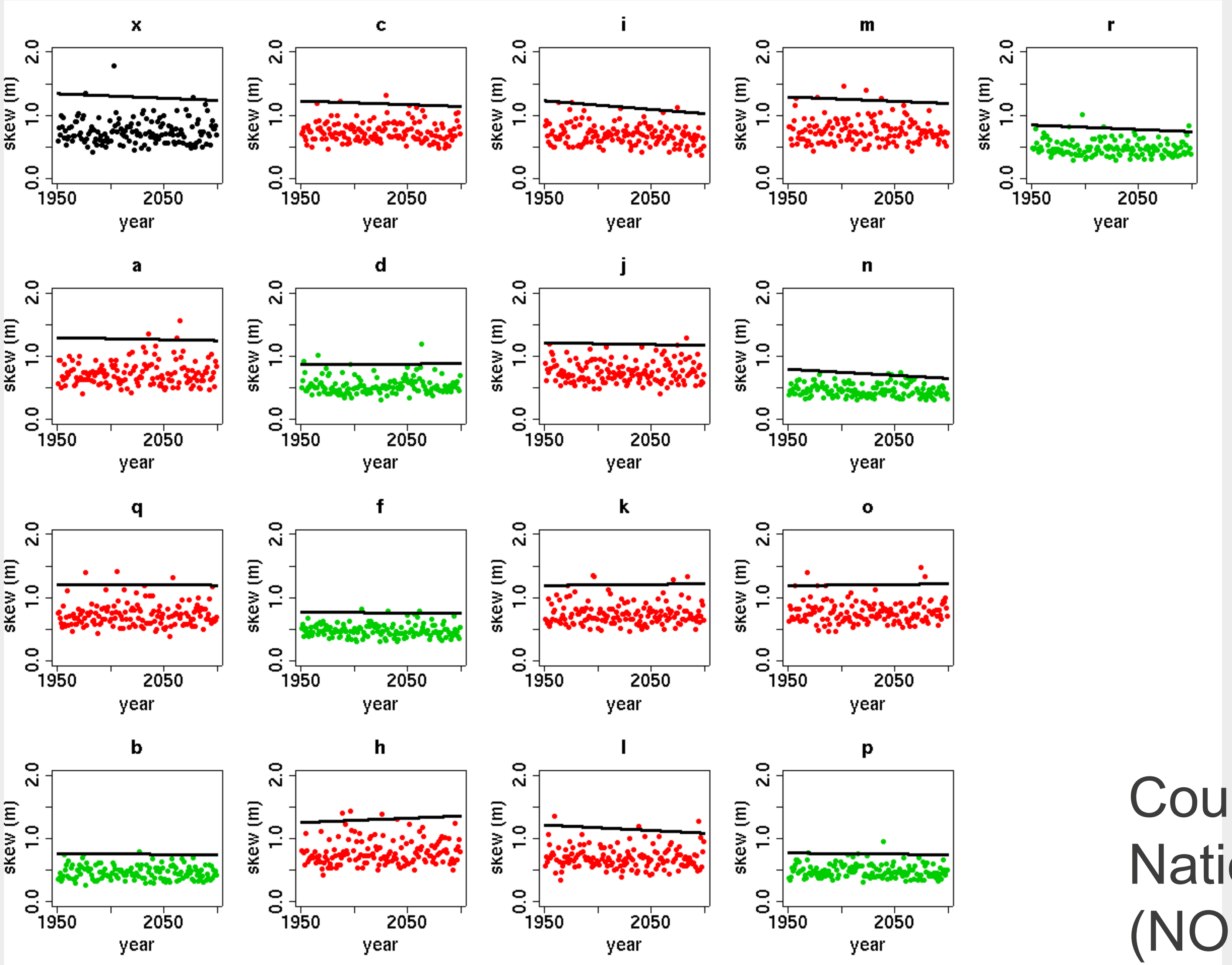
Courtesy of Stefan Laeger, Environment Agency

Climate change – Sea level rise

	Relative sea level rise from baseline (m)												
	2025			2055					2085				
UKCP09 Region	Medium p10	Medium p50	Medium p90	Low p10	Low p50	Medium p50	High p50	High p90	Low p10	Low p50	Medium p50	High p50	High p90
East Midlands	0.05	0.08	0.11	0.11	0.17	0.20	0.24	0.34	0.19	0.29	0.35	0.41	0.59
East of England	0.05	0.08	0.12	0.12	0.18	0.21	0.24	0.34	0.19	0.30	0.35	0.42	0.59
London	0.05	0.08	0.11	0.11	0.17	0.20	0.23	0.33	0.18	0.28	0.34	0.40	0.58
North East	0.04	0.07	0.10	0.08	0.14	0.17	0.21	0.31	0.14	0.24	0.29	0.36	0.54
North West	0.03	0.06	0.09	0.07	0.13	0.16	0.19	0.29	0.12	0.22	0.27	0.34	0.52
South East	0.05	0.08	0.11	0.11	0.17	0.20	0.23	0.33	0.18	0.28	0.34	0.40	0.58
South West	0.06	0.09	0.12	0.13	0.19	0.22	0.26	0.36	0.22	0.32	0.38	0.44	0.61
Yorkshire and The Humber	0.05	0.08	0.11	0.11	0.17	0.20	0.24	0.34	0.18	0.29	0.34	0.41	0.58
Wales	0.04	0.08	0.11	0.10	0.16	0.19	0.22	0.32	0.16	0.27	0.32	0.39	0.56

From UKCIP 09

Climate change - surges



Annual maximum surges and trend in 50-year return level at Sheerness from a 150 year run of a coupled GCM-RCM-surge model (MOHC-POL)

Courtesy of Kevin Horsburgh
National Oceanography Centre (NOC)

HR Wallingford
Working with water

Summary

- Extreme sea level analysis has been undertaken for many years.
- Tide/surge interaction is important
- Use of the skew surge is considered current best practice
- Combination of statistical models and numerical models used to provide estimates.
- Climate change
  - Future extremes to extremes - adding sea level rise to current extremes
  - Insufficient evidence for changes to surge levels

Acknowledgements

With thanks to:

Kevin Horsburgh - National Oceanographic Centre (NOC)

Stefan Laeger – Environment Agency

For provision of slides

HR Wallingford
Working with water

References

Graf J (1981) “**An investigation of the frequency distributions of annual sea level maxima at ports around Great Britain**” Estuarine, Coastal and Shelf Science, vol. 12 issue 4, , Pages 389–449

Dixon, M.J., Tawn, J.A. (1994) **Extreme sea-levels at the UK A-class sites: site-by-site analyses.** Proudman Oceanographic Laboratory, Internal Document, No. 65, 229pp.

Dixon, M.J., Tawn, J.A. (1995) **Extreme sea-levels at the UK A-class sites: optimal site-by-site analyses and spatial analyses for the east coast.** Proudman Oceanographic Laboratory, Internal Document, No. 72,

Dixon, M.J., Tawn, J.A. (1997) **Spatial analyses for the UK coast.**. Proudman Oceanographic Laboratory, Internal Document, No. 112,

Environment Agency (2011) **Coastal flood boundary conditions for UK mainland and islands,** ISBN: 978-1-84911-212-3

Questions

?

HR Wallingford
Working with water

Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom

1330 Avenue of the Americas Suite 23A, New York, NY 10019, USA

2800 Post Oak Boulevard Suite 4100, Houston, TX 77056, USA